PERFORMANCE EVALUATION OF MOBILE WIRELESS SENSOR NETWORKS UNDER UNCONTROLLED MOBILITY

BY

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To my family

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THESIS ABSTRACT

NAME: AHMED SAEED BINSAHAQ

TITLE OF STUDY: Performance Evaluation Of Mobile Wireless Sensor Networks Under Uncontrolled Mobility

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Wireless sensor networks (WSNs) consist of low powered devices that have a computation, wireless communication and environment sensing capability. These low cost sensors usually are deployed in a densely and stationary manner for periodic sensing of an environment phenomenon. These capabilities of WSNs open the door for many applications in military, health, industry and environment monitoring fields. Mobile Wireless Sensor Networks (MWSNs) is a subclass of WSNs in which some or all sensors are mobile. Many environmental monitoring systems are designed and deployed on top of MWSNs in which sensor hosts are uncontrolled (e.g. OpenSense system for Zurich city air pollution monitoring). In this thesis we evaluate the performance of mobile wireless sensor networks in which all sensors are mobile and uncontrolled. We consider two simple sensing schemes, *threshold-based and energy-aware. We also consider four different data delivery mechanisms mobile sensors can use for data delivery to the base-station; namely GPRS (General Packet Radio Service), Wi-Fi, Hybrid (GPRS and Wi-Fi), and Ad-Hoc in which two routing protocols, GPSR (Greedy Perimeter Stateless Routing) and AOMDV (Ad hoc On-demand Multipath Distance Vector routing), are used. We test the network performance through an extensive simulation based experiments using ns2 simulator. We find that MWSN performance is affected by the data delivery mechanism been used. Wi-Fi performance depends on available base-station(s) coverage. GPRS and Hybrid approach performs similarly and outperform other data delivery mechanisms. We also find that the addition of Wi-Fi in the Hybrid approach improved energy consumption. Both AOMDV and GPSR perform badly in low network density. GPSR, however, outperforms AOMDV in medium and high density MWSNs due to its advantage of using geographic information for packet routing which cuts the need for the expensive route discovery process used by AOMDV. The energy-aware scheme helps in extending network lifetime with a little degradation in system performance because sensors become more conservative when their energy starts to deplete.*

ملخص الرسالة

الاسم الكامل: أحمد سعيد بن سحاق

عنوان الرسالة: تقييم أداء شبكات الأستشعار اللاسلكية المتحركة تحت التنقل غير المنضبط

التخصص: شبكات الحاسب الالي

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تتكون شبكات الأستشعار اللاسلكية من أجهزة تعمل بطاقة منخفضة ولديها قدرات حسابية والقدرة على الاتصال اللاسلكي و إستشعار البيئة المحيطة. هذه الاجهزة ذات السعر المنخفض عادة ما تكون ثابتة ومنتشرة بكثافة للأستشعار الدوري للبيئة المحيطة. هذه الشبكات فتحت المجال للعديد من التطبيقات في المجالات العسكرية, الصحية و مراقبة البيئة. تعتبر شبكات الأستشعار اللاسلكية المتحركة صنف من شبكات الأستشعار اللاسلكية بحيث أن بعض أو كل أجهزة الأشتشعار تتحرك. العديد من أنظمة مراقبة البيئة صممت وبنيت بناء على شبكات الأستشعار اللاسلكية المتحركة بحيث أن المضيف لجهاز الأستشعار يتحرك بشكل غير منضبط (على سبيل المثال , نظام OpenSense لمراقبة مدى تلوث الجو في مدينة زيورخ السويدية). في هذه الاطروحة نقيم أداء شبكات الأستشعار اللاسلكية المتحركة بحيث أن أجهزة الأستشعار تتحرك بشكل غير منضبط. في هذه الأطروحة أجهزة الأستشعار تتستخدم طريقتين للأستشعار هما: *threshold-based* و *energy-aware*. أيضا أجهزة الأستشعار تستخدم أربع طرق لأرسال البيانات هم: GPRS (General Packet Radio Service) , Wi-Fi, (GPRS مع Wi-Fi) Hybrid, Ad-Hoc . أثناء أستخدام طريقة Ad-Hoc أستخدم بروتوكولين مختلفين لتوجيه حزم البيانات داخل شبكات الأستشعار اللاسلكية المتحركة هما: GPSR (Greedy Perimeter Stateless Routing) و AOMDV (Ad-hoc On-demand Multipath Distance Vector routing) . في هذه الأطروحة أجرينا تجارب مكثفة بإستخدام محاكي الشبكات *ns2* لتقييم أداء شبكات الأستشعار اللاسلكية المتحركة. بناء على تلك التجارب وجدنا أن أداء شبكات الأستشعار اللاسلكية المتحركة يتأثر بطريقة إرسال البيانات المستخدمة. أداء طريقة Wi-Fi يعتمد على مدى توفر محطات الاتصال وأستخدامها مع طريقة Hybrid حسن من أستهلاك الطاقة. البروتوكولات المستخدمة مع طريقة Ad-Hoc وهما GPSR و AOMDV يؤديان بشكل سئ عندما تكون شبكات الأستشعار اللاسلكية المتحركة قليلة الكثافة. لكن بوتوكول GPSR يتجاوز بروتوكول AOMDV في الأداء عندما تكون شبكات الأستشعار اللاسلكية المتحركة ذات كثافة متوسطة أو عالية نتيجة إستخدامه للمعلومات الجيوغرافية لتوجيه حزم البيانات وبالتالي يوفر عناء إستخدام طريقة البحث عن المسار أو الطريق التي يستخدمها بوتوكول AOMDV. إستخدام طريقة الأستشعار *energy-aware* ساعد في تمديد العمر الأفتراضي لشبكات الأستشعار اللاسلكية المتحركة مع نزول طفيف في أدا النظام بسبب أن أجهزة الأستشعار تصبح متحفظة عندما تبدأ طاقتها بالنفاذ.

CHAPTER 1

INTRODUCTION

Wireless sensor networks (WSNs) consist of low powered devices that have computation, wireless communication and environment sensing capabilities. Most of these networks are application oriented in which network static sensors are deployed and preplanned for the purpose of sensing the changes of an environmental phenomenon. Those sensors report to a data deposit node exists in the network field called sink or base-station node. Wireless sensor networks open the door for many applications in different fields such as military [8], industrial [9], and environmental monitoring [10][11][12]. For instance, Zebra Net system [10] (used for wild life monitoring) consists of sensors attached to wild animals. This system is used to collect information about animals and their traveling activities to help zoologists in studying and understanding animals behavior in wildlife. Similar system of habitant monitoring was conducted to monitor seabirds nesting environments and behavior of those birds using a wireless sensor network system [11]. Air quality monitoring is another application in which pollution levels are monitored in urban areas using Geo-sensor networks. Pollution alarms are issued according to safety levels which effects on human health [13]. Beside environmental monitoring applications, wireless sensor networks are used in many critical applications such in unmanned surveillance missions where involvement of humans contains high risks as it is the case in military surveillance missions or gathering information about enemy lines or in border areas [14].

1.1 Mobility in Wireless Sensor Networks

Wireless sensor networks usually consist of statically deployed sensor nodes monitoring surrounding environment and reporting to a stationary sink node through multiple hop data forwarding. However, in some WSNs, some nodes may have the ability to move from one location to another. This movement capability can be usefully (for the network benefit) and purposefully (based on commands) used. For example, sink node may move in the network field between static sensors [15],[16] to collect data. Sink movement prolongs the total network lifetime by balancing energy consumption between different sensors instead of sink node neighbors. Those sink's neighbors suffer because all network sensed data packets are forwarded to them before arriving destination (static sink node). Existence of controlled mobile nodes is not exclusive to mobile sink. Some wireless sensor networks contain few mobile nodes called data mules which move between static sensors to collect sensed data and deposit them in the sink node [17]. Those nodes usually are powerful in communication, computation and energy resources. Usage of data mules reduces energy consumed by sensors when they route packets to sink node. Data packets are sent directly by sensors to data mules, then relied to sink node instead of normal multi-hop routing. Even usage of data mules in WSNs prolongs network life time, but it has a side effect on data delivery delay since sensor buffer data until it can connect to one of those moving data mules. Therefore, sophisticated movement scheduling algorithms for data mules are required. Existence of nodes mobility in wireless sensor network may have some advantages such as extending network coverage [18] when nodes fail due to hardware faults or energy shortage. Also, sensing coverage can be extended to places where deployment of static or stationary sensors is impossible due to short time needed sensing coverage or deployment costs. For that purpose and differently than in mobile sink or mules, sensor nodes must have ability to move toward those sensory uncovered areas. Robomote [19] is a mobile platform designed with two motors and can carry a mote or sensor device. Motion of Robomote is controlled by mote device (e.g. MICA mote). Users can develop TinyOS application to manage Robomote movement behavior. Similiar to Robomote[19], a wheel-based robotic sensor node called RacemoteZ [20] is designed to monitor microclimate changes in dangerous environments that are inaccessible by human or large robots.

1.2 Uncontrolled Mobility in Wireless Sensor Networks

Instead of using motors for sensor movement (as in Robomote [19] for example), sensors can be attached to any moving object in the surrounding environment such as buses, cars, animals (e.g. as used in Zebra Net system [10]) and even people. Many monitoring applications incorporate community users in the sensing process. Instead of using a large stationary wireless sensor network, they use community members (people with sensing units) to support traditional stationary sensors. Common Sense [1] is one of those systems. Sensing units held by people are used to sense surrounding environment pollution levels and expose that data back to community users through a web portal. This community sensing has a big opportunity in environmental applications, especially with the rapid development in smartphone devices that contain many embedded sensors and their ability to interface with traditional sensors [21]. Many environmental monitoring systems depend totally on mobile sensors, as it is the case in OpenSense system [22]. Air pollution levels in Zurich city, Switzerland are measured using sensors attached to moving buses and trams. In this system sensor's mobility is not controlled by end user as its the case in Robomote[19].

Smartphones are used to get information that help disaster (e.g. earthquake) emergency units as it is the case in iShake system [23]. Embedded accelerometer sensors in smart phones are used for sensing motion produced by an earthquake and report directly to emergency systems to evaluate distribution of earthquake

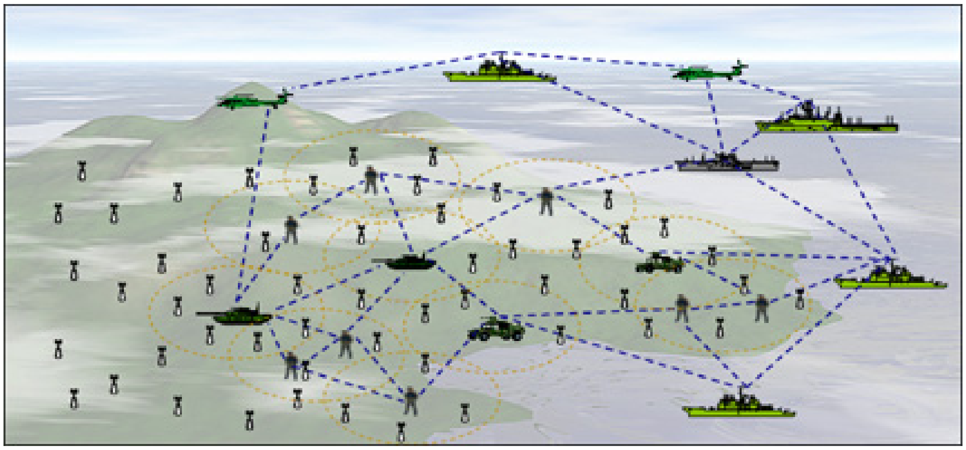


Figure 1.1: A mobile sensor network formed between military units

damages.

Existence of sensors mobility introduces new class of WSNs called Mobile Wireless Sensor Networks (MWSNs) [24]. OpenSense [22] and many other pollution monitoring systems [3] [25] deployed on top of such like MWSNs. Our focus in this thesis is on mobile wireless sensor networks in which sensor nodes are mobile and uncontrolled by end user as it is the case when sensors are attached to environment moving objects (such as vehicles) to become mobile sensors.

1.3 Research Motivation

Beside existing air quality monitoring applications, there are other fields that can benefit from mobile wireless sensor networks. For example, critical military missions usually consist of different types of units such as tanks, ships, planes, robots and soldiers. A mobile wireless sensor network can be formed between those collaborating units and a command center for the detection of enemy movements, border intruders and protection from possible threats. (see figure 1.1). In the industry, an early chemical leakage detection in industrial regions around big urban areas is a critical issue for governments due to large damage it can cause. Traditional sensors maybe only deployed in limited areas around factories. Exiting moving vehicles (buses, trams, taxis and police cars) can be used to monitor levels of chemical pollution in such areas and determining affected areas for fast decision making. Such systems will help in saving lives by issuing alarms in the right times, to the right people who might be affected.

We are motivated by above mentioned possible applications of Mobile Wireless Sensor Networks (MWSNs) and the works done in many environmental monitoring systems such as OpenSense project [22] or the works in [3],[25] where they used MWSNs to evaluate air pollution levels in urban areas. Despite potential applications of Mobile wireless sensor networks, usage of uncontrolled mobile sensors imposes many challenges on the success of those applications. Measurements taken by those sensors may be inconsistent due changes in sensors density caused by mobility. This may affect network application since a consistent flow of environmental measurements in a specific time intervals is required. Data delivery is also affected by sensors mobility where network nodes connectivity (linkage between nodes) may change from time to time. Also, data validity is tightly related to time especially for critical applications which make decision taking on which suitable data delivery mechanism a challenging task.

1.4 Thesis Objectives

Considering the above possible applications of mobile wireless sensor networks and challenges imposed by sensors mobility and applications requirements. Designing new protocols or implementing new application on top of mobile wireless sensor networks is a challenging task specially when sensors mobility is uncontrolled by end user. Therefore, in this thesis we investigate these challenges and study the performance of a mobile wireless sensor network with a location based application. In such application, sensing measurements are taken based on specific points of interests in a field determined by end users. We focus our study on usage of different sensing and data delivery schemes that maybe used in mobile wireless sensor networks and their effect on application performance. For performance evaluation, we used utility function to estimate sensors contribution to the network application and energy consumed by each sensor.

1.5 Thesis Contributions

The thesis contributions can be summarized in following points:

- Prepare a simulation environment for a mobile wireless sensor network with a location-based application.
- Study impact of sensors mobility behavior on application performance.
- Study different sensing schemes that can be used by mobile sensor.

- Study different data delivery mechanisms and their effect on network application success and suitability to be used in mobile wireless sensor networks.

- Evaluate usage of those sensing and data delivery schemes using extensive simulations.

- Evaluate the performance of mobile wireless sensor network in which sensors mobility is uncontrolled by end users.

1.6 Thesis Organization

This thesis is organized as in the following chapters. Chapter 2 starts with a background about existing mobile sensing systems from previous works. Comparison between these system is established according to many characteristics such as sensor mobility behavior, network application, communication models and location awareness. Chapter 3 discusses the system model used to simulate mobile sensor networks and deployed application. This model is used in experiments done in next chapters. Chapter 4 introduces two different sensing schemes, threshold-based and energy-aware sensing schemes and four different data delivery mechanisms that can be used by mobile sensing systems. We evaluate performance of mobile wireless sensor network using those sensing and data delivery schemes in chapter 5. Chapter 6 goes through the usage of two MANET routing protocol for data delivery in MWSNs. Finally, thesis is concluded in chapter 7 in which the overall performance of the evaluated mobile wireless networks is summarized with suggestions for future work.

CHAPTER 2

MOBILE SENSING SYSTEMS

In this chapter, we explore previous work done in the literature in the context of mobile sensor network systems. We classify the reviewed works on uncontrolled mobility in two paradigms, participatory and mobile sensing, based on the nature of mobile sensor involvement and commitment in the sensing process.

2.1 Participatory Sensing

Motivated by many promising environmental applications and the capabilities of new generation of mobile devices that could make them mobile sensors, participatory sensing is introduced by Burke et. al. [26]. In this model, data is gathered opportunistically by end users. Authors described a participatory sensing architecture called partisan that lets end users participate in the sensing process. This architecture is aimed to provide network discovery, naming and data dissemination services of many kinds of participatory sensing applications.

Many environmental monitoring applications can be classified as participatory sensing systems such as Ear-Phone [27], NoiseTube[28], CommonSense [1], N-SMARTS [29] and HazeWatch [30].

In Ear-Phone system [27], the authors use mobile phones to periodically (when phone is not busy and using the phone's mic) record noise levels. Noise levels are stored with GPS-Time stamp and then transmitted to central server. An application then analyze the data and draws a road noise pollutions map. This helps in measuring city noise levels faster than traditional way that depends on stationary measurements.

Similar to Ear-Phone [27], the authors of the NoiseTube [28] system use smartphone as mobile sensors to assess noise pollution in people environment (e.g. home, office, tram and bus stations). Each second a sample is recorded, Time-Location stamped, and sent using the smartphone to a central server. The noise pollution map is then drawn to reveal users exposure to noise pollution in their every day environment.

In Common Sense [1], the authors try to fill the gap caused due to sparsely deployed air quality monitoring stations by using monitoring devices held by individuals, as in Figure 2.1, to sense their environment and expose collected data to all community members through a web portal or mobile devices.

Similar to CommonSense[1], in N-SMARTS [29] the authors investigate ability to gather raw air pollution data using sensors attached to GPS-enabled cell phones. They develop a platform from sensors interfaced with smartphones to be used for air quality sensing.

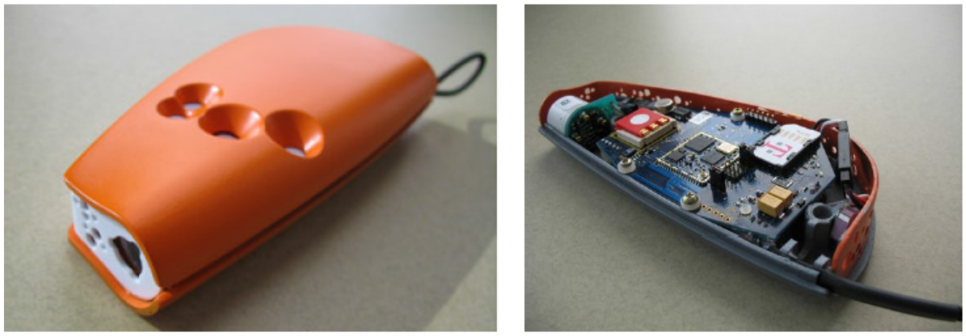


Figure 2.1: CommonSense monitoring handheld devices [1]

In HazeWatch [30] system, the authors use portable sensor units attached to cars to monitor air pollution as users drive. Air pollutants such as carbon monoxide (CO) and nitrogen dioxide (NO_2) is measured by sensing unit and sent to the driver's mobile phone through a Bluetooth module. These measurements are Location-Time stamped and are sent directly to a cloud server by the mobile phone. A map of pollution levels is generated and pollution information is distributed back to individual users.

When Burke [26] introduced participatory model, mobile phones were not powerful as they are these days. Beside their location awareness (GPS/GLONASS), computation and communication capabilities, new emerging smart phones contain many embedded sensors such as Accelerometer, Geomagnetic, Proximity, Gyroscope, etc [31]. Also, external traditional sensors, if needed, can be interfaced to those smartphones. In [21] for example, the authors incorporate community in the sensing process by using sensors attached to smartphones held by moving people. The authors plugged an Ozone sensor with a smartphone to produce a GasMobile device. This device is used by bicycle riders to periodically measure the air quality. Measurement are GPS-Time stamped and sent directly to a monitoring

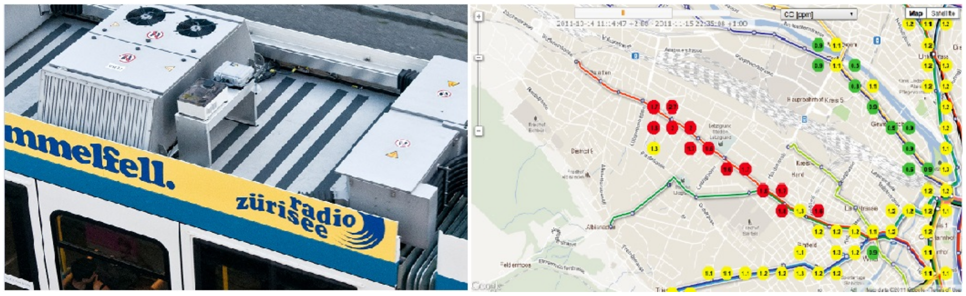


Figure 2.2: Sensor board on tram and city CO pollution map from OpenSense system [2]

server.

Devices with such features can be used in the design and implementation of many location based sensing applications. For example a smartphone can be configured, using proximity alert feature, to take an image whenever its user go through a specific location(s).

Although participatory sensing has an advantage of acquiring large amounts of data in a simple and cost efficient way using community members, it suffers from a problem which is that end users are not always willing to participate in the sensing process. Our system model is similar in the concept of participatory sensing by using mobile nodes to sense the surrounding environment. However, in our case these devices are committed, when needed, in doing sensing tasks for the success or satisfactions of network application. This is not the case in participatory sensing model in which users are voluntarily participate in data gathering.

2.2 Mobile Sensing

Many sensing applications exist in dynamic environments that contain naturally moving objects. OpenSense project [32][22] is an obvious example of exploiting surrounding mobile objects such as buses and trams for environment sensing. OpenSense [22] is deployed in the city of Zurich, Switzerland at the end of September 2011 [2]. In that system, a board of sensors deployed on top of moving buses and trams through the city to gather data about air quality. Measurement of emitted gases (e.g. Ozone O_3, nitrogen dioxide NO_2, nitrogen monoxide NO and sulfur dioxide SO_2) and fine particles concentration in the city air are collected. These collected measurements are used to draw a real time and historical map view of air quality (air pollution levels) in the city as in Figure 2.2.

Authors of [33] combine user activity sensing through sensors built in mobile smartphones with air quality mobile sensing systems such as OpenSense [22] to find out whether people daily actives can expose them to air pollution.

One of the early mobile sensing systems is CarTel [34]. CarTel consists of units for collecting sensing data and opportunistically (e.g. *Wi-Fi*) sending the collected data to a back end servers. CarTel units send data either through open *Wi-Fi* access points or through other CarTel nodes (cars) to relay data to background servers.

Similar to OpenSense [22], an air pollution monitoring project is conducted in Sharjah city, UAE [25]. They used three pollutant sensors (carbon monoxide CO, nitrogen dioxide NO_2, and sulfur dioxide SO_2) and the measurements are directly

Figure 2.3: Real-time vehicular mobile sensing box and heat map of Carbon Monoxide concentration [3]

sent through GPRS (General Packet Radio Service) connection to an air pollution monitoring server.

Another air quality vehicular based project in [3] monitors air pollutants such as carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x) emitted from vehicles to city air. The authors develop two mobile sensing models, one for public transportation such as buses or cars (Figure 2.3) which similar to sensing board in OpenSense [32][22]. The other model is for personal usage such as air-quality aware drivers in which the driver can connect a personal sensing unit with his/her smartphone and get involved in a participatory sensing process similar to CommonSense [1] or HazeWatch[30] projects.

Instead of fixed air quality stations, an air quality monitoring is carried using Vehicular Sensor Network (VSN) in Palermo Italy [6]. Public transportation buses are used instead of cars which was used in CarTel [34]. Each vehicle (bus) is equipped with a sensing unit for air pollutants (e.g. NO2,CO2 and CO), temperature and humidity. Measurements are periodically collected and sent. Each sensing unit works in store-and-forward fashion where collected data are buffered until the vehicle meets an access point. Then, data is forwarded to central server for more analysis and minig. Access points are positioned in road intersections and traffic lights.

In OpenSense [32][22], sensors (buses with sensing units) move according to predetermined Time-Route table (bus, tram travelling path) performing periodic sensing which is also the case in Ear-Phone [27] in which mobile sensors move beside traffic roads.

OpenSense [32][22] authors exploited the pervious knowledge of time and path to get optimal sensing scheme, OptiMos [32], which can be used to reduce the sampling rate. This prior knowledge does not exists in our case were mobile sensors move randomly in the sensing area. Table 2.1 provides a summary of previously mentioned systems with a simple comparison of how they work. Most of the above works assume that sensors are aware of their locations and can directly send collected measurement (e.g. 3G/GPRS).

In this thesis, we use similar assumptions to study different sensing and data delivery mechanisms in a totally mobile, and uncontrollable wireless sensor networks.

Table 2.1: Comparison of mobile sensing systems

Paper Work	Host Object	Sensor Type	Sensing Scheme	Data Delivery	Location Awareness
CommonSense [1]	People	Hand held devices	Participatory	GPRS	GPS
Ear-Phone [27]	People	Mobile Phone Mic	Phone not used	Open Wi-Fi APs, maybe 3G	Phone GPS
HazeWatch [30]	Cars	Air pollutants sensors	When user drive	GSM	Phone GPS
OpenSense [22]	Buses, Trams	Air pollutants sensors	Location-Time table	GSM	GPS
Sharjah [25]	Buses	air pollutants sensors	Threshold based	GPRS	GPS
MAQUMON [35]	Cars	Air pollutants sensors	Periodically	GSM	GPS
GasMobile [21]	Bicycles	Ozone sensor	Every 5 seconds	3G	phone GPS
[3]	Cars, Buses	Air pollutant sensors	Every 5 seconds	3G/GPRS	GPS
VSN [6]	Buses	Air pollutant sensors	Periodically	Wi-Fi APs	GPS
CarTel [34]	Cars	GPS data	When user drive	Wi-Fi APs Other CatTels	GPS

CHAPTER 3

SYSTEM MODEL

In this chapter, we define the model we use in our experiments. We discuss the sensing platform we used to model sensor nodes, the assumed network application and the mobility pattern that mobile sensors follow.

3.1 Network Model

We assume that the network application is designed for an event detection such as chemical leakage or fire detection in specific locations. The mobile wireless sensor network consists of a set $N\{S_1, S_2, S_3, ..., S_n\}$ of randomly moving sensors. Main application (e.g. chemical leakage or fire detection) is divided into set $J\{M_1, M_2, M_3, ..., M_J\}$ of location-based missions or points of interest.

We adopt the definition used by Rowaihy et. al. [36], which is: "a primitive sensing task defined by specific geographic location that requires information, which maybe contributed by one or more deployed sensors". A mission represents a data request or command to collect sensing measurements from that location

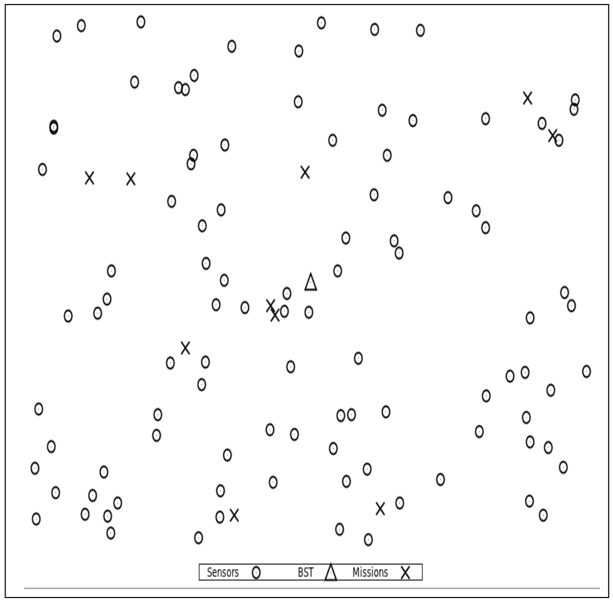


Figure 3.1: Network model. 100 Mobile sensors, 10 missions and one base-station.

by all surrounding sensors. These requests can be changed based on new user requirements. Collected measurements are transfered to a base-station or sink node. The Number and locations of missions are user parameters. Figure 3.1 shows a sample network view in which circles represent mobile sensors and x-marks are points of interest or missions that need to be sensed according to user requirement. In our model network has one base-station in the center of the field. We can imagine this environment as in a chemical factory campus or big construction site in which mobile sensors are attached to workers, vehicles, or any moving object. Missions' locations represent points of interest that need to be checked for any leakage.

Every sensor in the network moves randomly according to its host object's behavior. It also senses missions within a specific sensing range, buffers those generated measurement data, and deposits them to the base-station when it is possible. When data is received by the base-station, it can be used by the application layer to do draw a pollution levels map, for example. The utility provided by a mobile sensor to a specific mission represents the probability of event detection at that location or the quality of information received from that sensor. In most cases, this utility is affected by sensor type (e.g. camera with zooming capability) and distance between that sensor and the event location. For instance, measurements taken by sensors near a gas leakage will be more accurate (for gas leakage detection) compared to measurements taken by sensors located on farther locations.

At each time unit, a single mission, M_j, may receive utility from one or more sensors. The utility received by M_j which we denote as u_j is defined as follows:

$$u_j = 1 - \prod_{S_i \to M_j} (1 - e_{ij}) \tag{3.1}$$

where e_{ij} is the utility contributed by sensor S_i to mission M_j which represents the event detection probability at mission's location. The product inside the brackets represents the the probability that the event is not detected by sensors surrounding mission M_j. Therefore, utility received, u_j, by mission M_j is one minus the product i.e. the probabilities that the event is detected. The main network goal is to maximize the average utility received by each mission or what we call network utility and denote as U. Hence, U is defined as follows:

$$U = (\sum_{j=1}^{J} u_j)/|J| \tag{3.2}$$

where u_j is the utility received by mission M_j (see equation 3.1) and $|J|$ is the size of set J which includes all missions. In this model, the system's performance depends on the amount of utility received by each mission and the number of missions that have been covered.

At any point in time, some missions may receive utility from mobile sensors and others may not (e.g no nearby sensors are available) which will be reflected on the success of these missions at that time unit. Mission success depends on the amount of utility it gets from network sensors and the time it take the measured data to be received by base-station. Data received after certain time period, T, from its generation or measurement time is useless. This time interval is a user parameter and represents the period of time data still valid and can be used. We call it *the deadline interval*.

Most of the previously reviewed works assume unlimited direct wireless connection, in which sensors use *3G/GPRS* connections to send data to back end servers [32][22][27][1][21][25][3]. However, other systems like *CarTel* [34] and the VSN [6] use opportunistic connectivity either through *Wi-Fi* access points or data mules (other CarTel nodes) for data delivery. In these systems, data packets are buffered temporally until sensor node finds an access point or another node to relay packets to the base-station. Therefore, in next chapter we will go through different data delivery mechanisms similar to those used in reviewed mobile sensing systems in Chapter 2.

Table 3.1: Sensor node characteristics in behave of Waspmote sensor platform

Sensors	Temp, Carbon Monoxide, Atmospheric Pressure
Sensing range	40 meters
Sensing energy consumption	12 mA (5V)
Communication range	80 meters
Wi-Fi Data Rate	2 Mbps
Wi-Fi Tx energy consumption	38 mA (4.2V)
Wi-Fi Rx energy consumption	38 mA (4.2V)
GPRS Data Rate	42.8 Kbps
GPRS TX energy consumption	1.4 A (4.2V)

3.2 Sensor Node

In any wireless sensing system, design and configuration of sensor node depends on the application. In order to be more realistic, we model sensor nodes in our system based on *Waspmote* [4] sensor platform (Waspmote is Libelium's advanced mote for Wireless Sensor Networks). Figure 3.2 shows how a *Waspmote* looks like.

We assume that sensor board consists of three sensors, Temperature, Carbon Monoxide (CO) and Atmospheric Pressure Sensor [37] as these sensors can be used for fire detection. To make our simulation based experiments more realistic we use similar specifications of these sensors such as the size of generated data and the energy consumption. Each sensor node contains two communication modules. A GPRS (General Packet Radio Service) connection module for directly sending data packets to base-station similar to *OpenSense* [32],[22] and many other mobile sensing systems [3],[25] and another *Wi-Fi* communication module similar to CarTel[34] or VSN[6] systems. Table 3.1 contains characteristics on which we model our sensor nodes.

(a) WaspMote (b) Sensor Board

Figure 3.2: WaspMote sensor node [4].

3.3 Mobility Models

Behavior of mobile sensor depends on its moving host object (e.g. vehicles, or people) which meas that sensors movement is uncontrolled. To imitate the behavior of real life moving objects we use two different mobility models, Random WayPoint [38] and Reference Point Group Model [39].

Random Way Point (RWP) [38] is a famous entity based mobility model in which a mobile node starts moving to a random destination within field area with a uniformly distributed speed between two values, minimum and maximum speeds. When a node arrives to the destination and before it chooses another destination, it stops for a specific pause time. Then it continues its journey to a new destination with a new direction and speed. People movement can be modeled with such model.

Reference Point Group Model (RPGM) [39] is a group based model. Group nodes move based on a movement path of a logical center (reference node) of that group. Independently from other members within the group, mobile node adjusts its movement based on the movement of the reference node. Pause time for all group nodes is the same as the reference node. Disasters surveillance groups of medical teams, groups of soldiers in military tactical missions, or tourists groups in city tours can be modeled by this model.

3.4 Other Assumptions

We build our system model based on few assumptions and we need to make them clear in this section. We assume that each mobile sensor knows its geographic location using any localization mechanism (e.g. GPS). This assumption is necessary in our model since we use a location based sensing application. Also sensors know locations of missions which can either be initially configured or on the fly based on user requirements. Sensors are omni-directional, i.e. they can sense and measure multiple directions at the same time. For example, gas sensors can sense all the surrounding environment at once. Therefore, utility contributed by a single sensor can be used by all missions within its sensing range.

CHAPTER 4

SENSING AND DATA DELIVERY SCHEMES

In this chapter we discuss the sensing and data delivery schemes that we propose to be used in mobile wireless sensor networks with uncontrolled mobility.

4.1 Sensing Schemes

During network life time, each sensor tries to serve missions within the field as it is configured. Each sensor evaluates its expected contribution for surrounding missions, e_{ij}. Behavior of sensor toward these missions depends on sensing scheme it follows. In the following we explain two sensing schemes: *threshold-based* and *energy-aware*.

4.1.1 Threshold-Based

Before sensors deployment in the network field, they basically configured with a sensing scheme. For instance, in temperature or humidity sensing application, user may only be interested when temperature or humidity values are above normal or a specific value. This unusual value may indicate something wrong such as fire has happened or would happen. In our system model, we use a binary threshold based sensing scheme. In this scheme, each sensor is initially configured with a specific utility sensing threshold. Therefore, for sensor S_i to sense mission M_j, its expected utility e_{ij} contribution must be above a certain sensing threshold τ. Sensing threshold, τ, is a user defined parameter depends on the level of sensory information quality the user is interested in. However, sometimes the end user may demands any utility values, in which case the sensor sense every mission in its sensing range. In this scheme, the sensor becomes $Naiive$ and will have no consideration for the expected utility it may contribute. This $Naiive$ scheme will have the highest energy consumption (sensor sense every mission it meets). A sensor can conserve more energy when higher thresholds are used.

4.1.2 Energy-Aware

Energy is a major issue in sensor networks since each node is initially supplied with a limited battery capacity and replacement of dead battery may be impossible. Therefore, each sensor needs to keep attention to energy consumption to prolong the network life time. This is especially true when these sensors work in unmanned environments. Threshold based sensing scheme does not react to changes in sensor energy levels. Therefore, we propose an energy aware scheme in which sensor adapts it sensing threshold based on its fraction of remaining energy, f. This new threshold, r, us defined as follows:

$$r = \tau^{f} \tag{4.1}$$

The expected utility contribution, e_{ij} the sensor S_i provides to mission M_j, will be compared with r instead of τ which is the basic sensing threshold defined above. Therefore, the sensor changes its sensing threshold as a response to energy decrement. As more energy gets consumed, a sensor becomes more conservative in sensing surrounding missions and will only sense missions with higher and higher utility.

4.2 Data Delivery Schemes

Each generated sensory measurement need to be delivered successfully to the base-station to be used by system end users (e.g. draw city pollution map). Therefore, network connectivity (i.e. connection between sensor nodes and base-station) plays a major role in network application success.

In previously reviewed works, in Chapter 2, different communication models are used by these mobile sensing systems. In this section we assume different mechanisms mobile sensor can use for data delivery to the base-station. We con-

Sensing Application
IP
SNDCP
LLC
RLC/MAC
GSM RF

Figure 4.1: The GPRS protocol stack [5]

sider four schemes ; namely *GPRS*, *Wi-Fi*, *Hybrid*, and *Adhoc*.

4.2.1 GPRS

OpenSense [22][32] and many other mobile sensing systems (such as [3],[25]) assume that data packets are directly sent from sensor nodes to back end servers using 3G/GPRS data connection. To model GPRS connection, we assume an ideal case in which there is no collision or interference.

Sensor generated data frame is folded inside an IP packet as it is specified in the GPRS protocol stack [40] (see Figure 4.1) and sent directly to base-station (network tower). In mobile sensing system, a data frame is produced after the sensing process contains measurements from all used sensors as in Table 3.1. According to *Waspmote* binary frame format [41], a 51 byte sized frame is produced if these three sensors (Temperature, Carbon Monoxide (CO) and Atmospheric Pressure) are used in addition to GPS coordinates for positioning. We reserve more 17 bytes for future use if more sensors are added or sensor needs to pass more information to the base-station node. Therefore, packet payload consist of

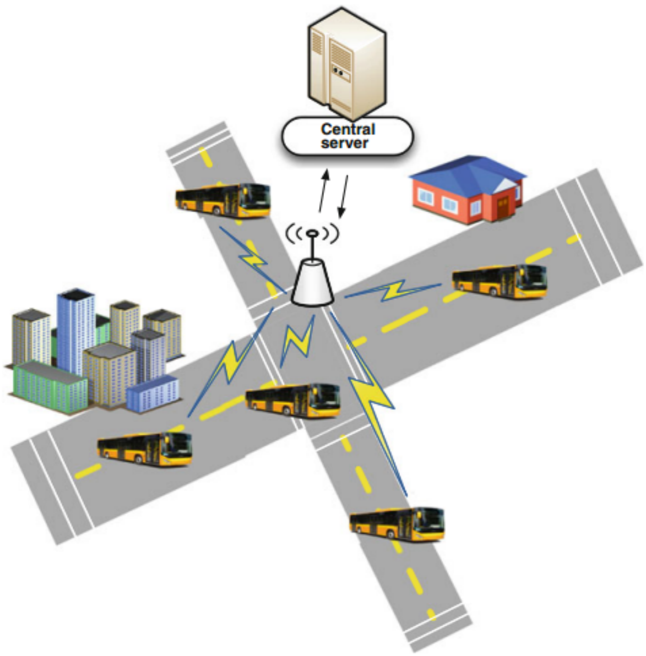


Figure 4.2: Direct Wi-Fi communication [6]

68 bytes. We use an up-link data rate equals to $42.8Kbps$ as it is specified by SIM5218E [42] cellular shield for a GPRS connection. For energy consumption we assume worst case in which sensor node sends data using peak current level it could reach when communicating with carrier according to SIM5218E [42] celluar shield used with *Waspmote* nodes [43] as specified in Table 3.1.

4.2.2 Wi-Fi

CarTel [34] and VSN [6] systems use opportunistic connectivity such as Wi-Fi access points or data mules (i.e. other *CarTel* nodes) for sending collected sensory data to back end servers (see Figure 4.2). In our system, beside GPRS communication module, each mobile sensor node is equipped with a Wi-Fi communication module. Therefore, sensor node can send data directly to any access point it

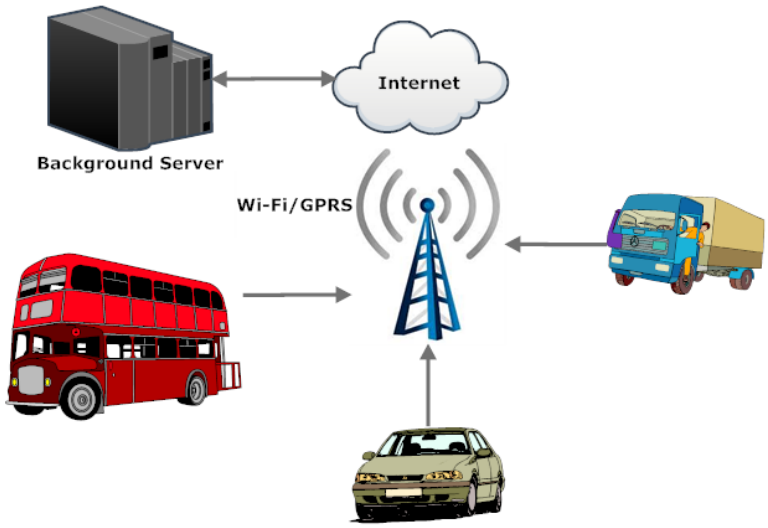


Figure 4.3: Hybrid approach. GPRS and Wi-Fi communication coverage

meets while it is moving. We assume that sensor sends data packets using Wi-Fi module according to IEEE 802.11a protocol standard. Unlike using direct GPRS connection, generated sensory measurements may be buffered for some time since mobile sensor may not always find an access points. For energy conservation, we assume that data packet buffered for period of time longer than deadline interval (T) will be discarded from sensor buffer as they will no longer be useful. In this scheme there might be a delay as full coverage of Wi-Fi access points is not always available.

4.2.3 Hybrid (GPRS and Wi-Fi)

In the previous schemes, we assume that a mobile sensor may use GPRS or Wi-Fi connection to send data packets. In this hybrid scheme mobile sensor can use both communication modules (GPRS and Wi-Fi) interchangeably based on the communication coverage sensor is within as in Figure 4.3. However, due to expected high energy current when GPRS connection is used, we assume that Wi-Fi has higher priority. Smartphones, when used as sensors, is a real example of such scenario. In the Wi-Fi scheme, a sensor node waits until it finds an access point to send its buffered data packets. In this scheme, however, whenever a new measurement is collected, if the sensor node is within coverage of any Wi-Fi access point it choses to send the measurement through it, otherwise the sensor node uses GPRS communication module to send the data directly to back end servers. We expect in this scheme that all generated data packets sent with a negligible delay since sensor node always have a choice to send either through GPRS or Wi-Fi modules. We considered this communication approach due that some sensing application may use smartphones as mobile sensors similar to the work done in [21] in which the authors plugged an Ozone sensor with a smartphone. Even the authors assume that data is sent directly using 3G connection, however, Wi-Fi connectivity can be used when users are inside building (home or work).

4.2.4 Ad-Hoc

In this scheme, mobile sensors form an ad-hoc network among themselves using the Wi-Fi communication modules. Therefore, data packets can be forwarded in a multi-hop fashion toward base-station node. Many routing protocols are developed for wireless sensor networks. Most of these routing protocols, however, are specifically designed with the assumption that network sensors are static [44] which is not the case here where the network consists of mobile sensor nodes.

Due to similarity between MANET (Mobile Adhoc NETwork) [45] and MWSNs (mobility of network nodes), existing MANET routing protocols can be used for this purpose since they are designed to work in totally mobile ad-hoc networks. We use two MANET routing protocol, Greedy Perimeter Stateless Routing Protocol (GPSR) [7] and Ad-hoc On-demand Multipath Distance Vector (AOMDV) [46].

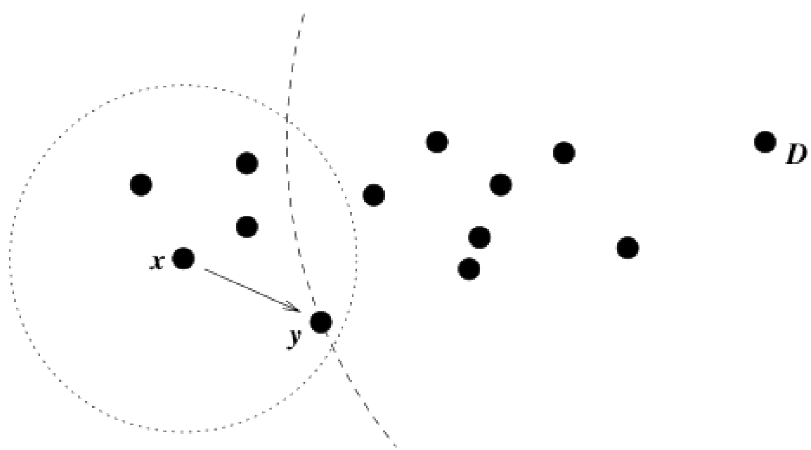
Greedy Perimeter Stateless Routing (GPSR)

Greedy Perimeter Stateless Routing (GPSR) [7] is a location-based routing protocol which assumes that each routing node knows its geographic location (e.g. using GPS). Each node announces its existence by broadcasting periodic beacons (i.e. proactive before any traffic start) to its one-hop neighbors. Each beacon contains the node's ID (e.g. IP address) and its geographic location. Using information (locations and IDs) from received beacons, each node forms a list of its one-hop neighbors. This list is kept valid only for a specific period of time. GPSR uses greedy forwarding to route data packets to their destined nodes as in Figure 4.4a (GPSR also assumes knowledge of destination's location). GPSR greedily forwards a packet from source node (**x**) to the closest next hop (**y**) to destination node (**D**). Sometimes greedy forwarding becomes impossible as in Figure 4.4b in which no neighbor node is closer to destination than source **x** to destination **D**. Therefore, GPSR tries to go around void area (i.e. area in which no nodes closer to destination than source). Then data packet is forwarded using perimeter nodes (**w** then **v** or **y** then **z**) as in Figure 4.4b. **D** is the destination and **x** is the node where the packet enters perimeter mode. Packet follows a path formed by perimeter forwarding. Whenever greedy forwarding is possible, then packet is forwarded according to greedy forwarding again.

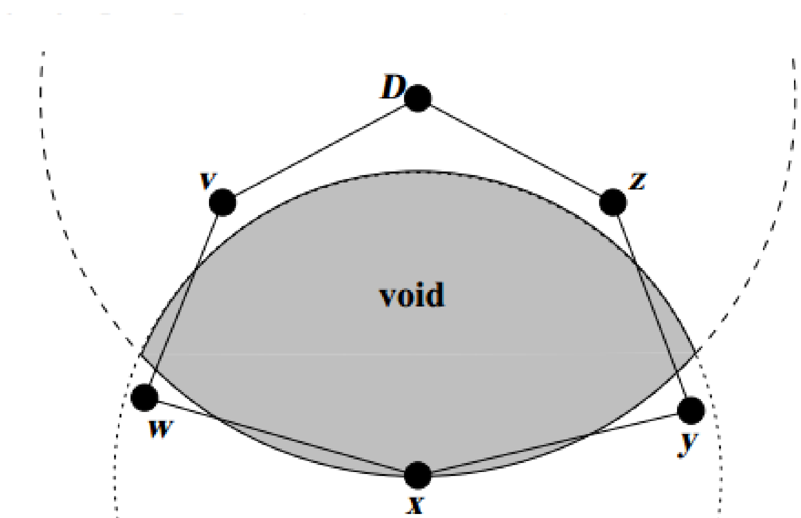
In GPSR, beside knowledge of its location, each source node need to know location of destination node (base-station in our case) and a list of its one-hop neighbors locations and IDs.

Ad-hoc On-demand Multipath Distance Vector (AOMDV)

AOMDV [46] is built based on AODV [47] routing protocol. It uses similar route discovery procedure used by AODV. AODV is a reactive routing protocol in which it start route discovery process only when there is a traffic to destination. Source node floods the network with a Route Request (RREQ) messages to destination marked with a unique sequence number. Intermediate node broadcasts this request message unless it has a valid and fresh route to destination, then it sends a Route Reply (RREP) message to the source node. Intermediate node records previous hop RREQ message is received from to form a reverse path toward source node. Duplicate RREQ messages are discarded by intermediate nodes. When the first RREQ message reach destination node, it sends back a RREP message toward source node following the same reverse path formed by intermediate nodes during the discovery process. Destination discards any received duplicate RREQ messages (see Figure 4.5a). The problem with AODV, it builds a single route path toward destination. When this route fails, another route discovery is needed. Therefore, AOMDV is designed with the main goal is to setup multiple routes

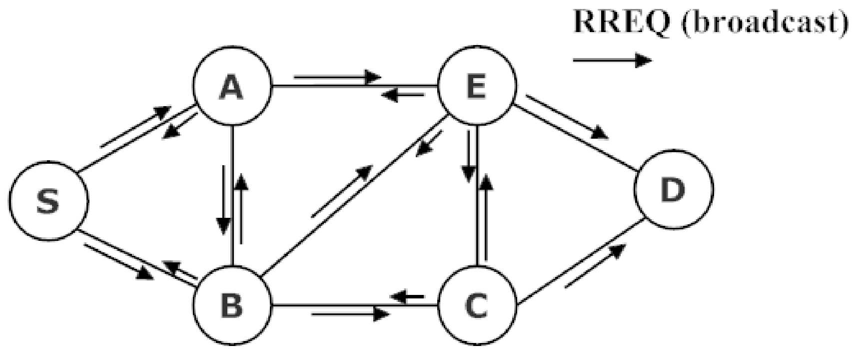


(a) The GPSR greedy forwarding.

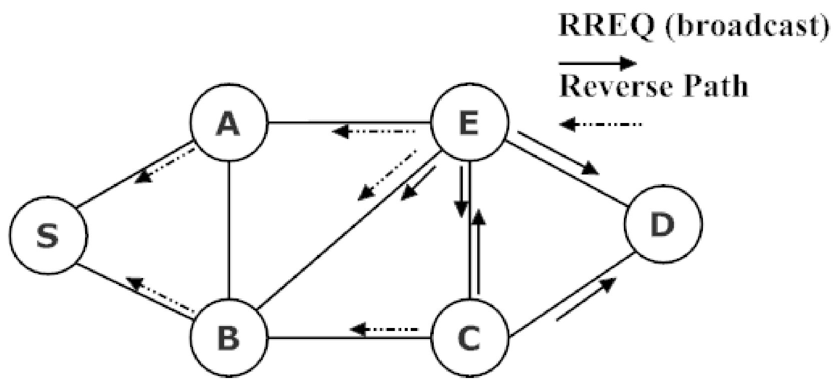


(b) The GPSR greedy forwarding fails.

Figure 4.4: The GPSR routing protocol. [7]



(a) RREQ messages broadcast.



(b) Reverse path formation.

Figure 4.5: The AOMDV route discovery.

within the same route discovery process (see Figure 4.5b). AOMDV exploits these duplicated RREQ messages to build multiple, loop free and link-disjoint paths within source and intermediate nodes. Destination node send RREP message to each RREQ message received from a different hop (unlike AODV in which destination discards other received RREQ messages after it sent the first RREP message). This provides alternative paths to destination and the route discovery is needed only when all these routes fail. The authors of AOMDV use HELLO messages to detects links break which is optional in AODV protocol. AODV protocol [47], has been studied in [48] to work in mobile wireless sensor networks. The authors claim that AODV is not suitable to work on MWSNs cause it is unable to detect broken routes and react quickly to topology changes in mobile environments. Therefore, we use AOMDV[46] routing protocol which is similar to AODV, but performs better than AODV as its authors claim.

In general, AOMDV is a reactive protocol, however, addition of HELLO message for down link detection is a proactive procedure similar to GPSR beacons. We use both routing protocols, GPSR and AOMDV, as ad-hoc options for data delivery in MWSNs.

CHAPTER 5

EVALUATION OF SENSING AND DATA DELIVERY SCHEMES IN MWSNS

In this chapter we evaluate performance of a mobile wireless sensor network with an event detection (e.g. chemical leakage or fire detection) application as discussed in Chapter 3. Network sensors use different sensing and data delivery schemes as discussed in Chapter 4. We focus on two metrics: average utility received by a mission and average node energy consumption by running different sets of experiments.

Table 5.1: Simulation parameters

Parameters	Values
Mobility model	RPGM/Random WayPoint(RWP)
Simulation area	(400 X 400) m^2
# of nodes	10,50,100,150,200,250
Packet payload	68 byte
Sensing rate	Every 5 seconds
# of missions	30
Time to live (Deadline)	20 seconds ($T = 20$)
# of base-stations	1, 4, 9
Max Pause time	20 seconds
Minimum node speed	0.5 meter/s
Maximum node speed	10 meter/s
Simulation time	1800 seconds

5.1 Simulation Setup

We use the *ns2* simulator [49] to evaluate the network performance. This simulator is used in many research works in the field of Adhoc and Wireless Sensor Networks and it supports node mobility. For sensors mobility, we use the *Bonnomotion* tool [50] to generate mobility files. These files are integrated within *ns2* simulation. Table 5.1 contains the simulation parameters. As in Section 3.1, all missions are modeled as an event detection [51][52] such as chemical leakage or fire detection for alarm monitoring systems. The utility function we use to model the utility provided by sensor S_i to mission M_j is defined as follows:

$$e_{ij} = exp\left(log\left(P_{FA}\right)\left(1 + \frac{SNR_1}{D_{ij}^2}\right)^{-1}\right) \tag{5.1}$$

where P_{FA} is the false alarm probability (user chosen parameter) and SNR_1 is the signal to noise ratio at a distance of one meter from the source signal. Utility e_{ij}

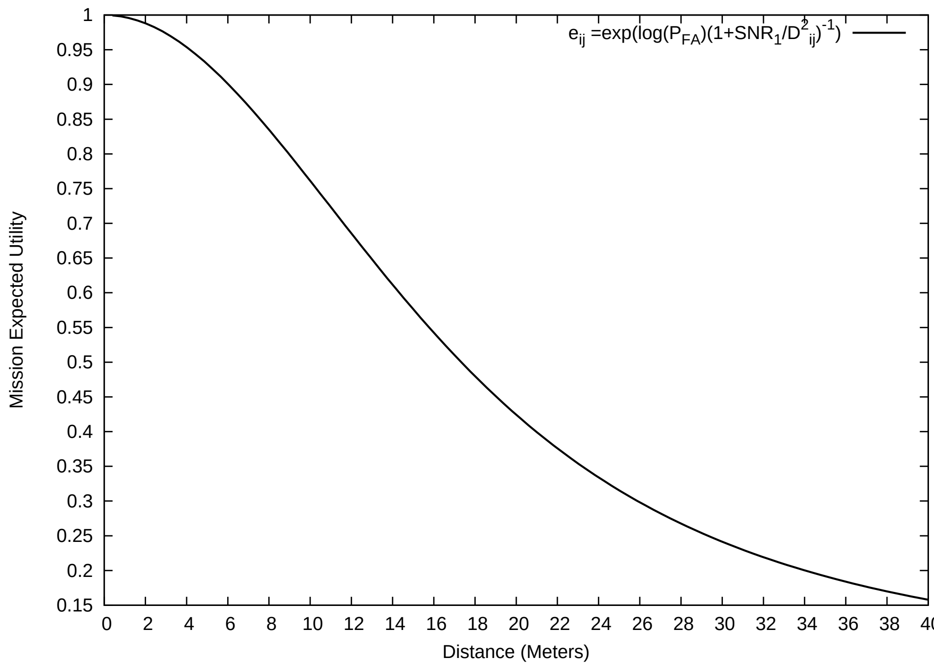


Figure 5.1: Expected utility contribution (e_{ij}) according to the distance (D_{ij}) between sensor S_i and mission M_j.

represents the probability of event detection by sensor S_i at mission M_j location. D_{ij} is the distance between sensor S_i and mission M_j at sensing time. We chose to use this formula as in [51][52], however, other functions can be used to model sensor to mission utility. Figure 5.1 shows expected utility according to distance between a sensor and mission. Missions are uniformly distributed within (400 X 400) square meters field area with one base-station positioned at the center. While sensor is moving and based on its sensing rate (every 5 seconds), it evaluates the expected contribution, e_{ij}, for surrounding missions as in equation 5.1. Sensor opens it sensing unit for one second to sense a mission. Utility set to zero when the distance, D_{ij}, between a sensor and mission, becomes greater than its sensing range. P_{FA} and SNR_1 were set as 0.001 and $30dB$ respectively. These two values are used only for testing and may not exactly model the behavior of a sensor type.

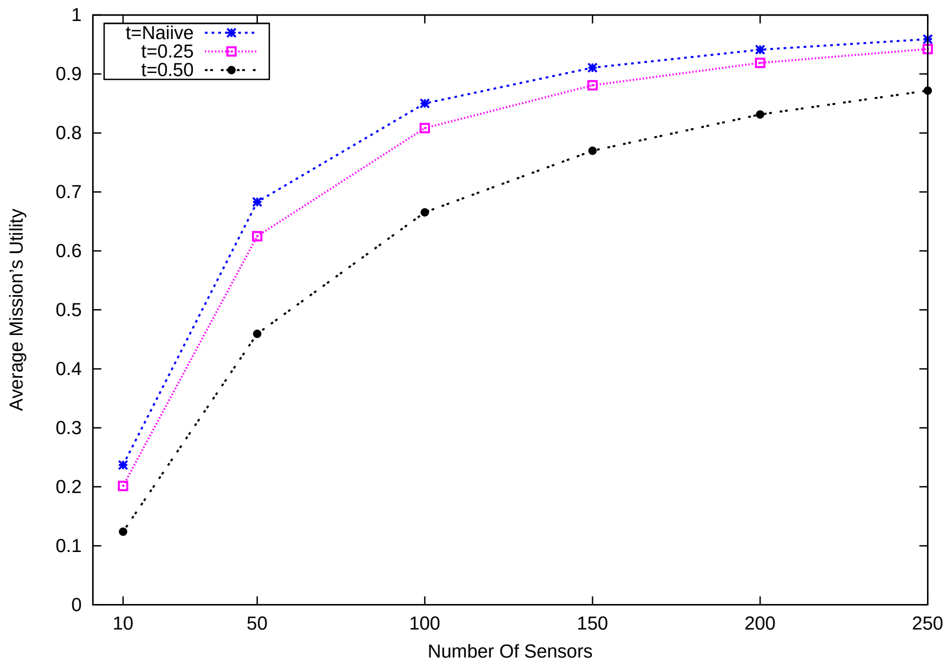


Figure 5.2: Average Mission 's Utility vs Node Density. RWP mobility model with 30 Missions and GPRS connection

We assume that data packets received after 20 seconds are discarded (i.e. $T = 20$ seconds). Measurements are also discarded from a sensor's buffer after 20 seconds from its generation. Communication range of sensor node and Wi-Fi access point set to 80 meters. We set it smaller than used by *Waspmote* Wi-Fi communication model [53] in which sensor can send up to 100 meters. We run set of experiments for evaluating network performance. Obtained results are taken based on network running on period of 1800 seconds and averaged over 30 runs.

5.2 Results and Discussion

5.2.1 Utility vs Node Density

In the first set of experiments we study the average utility received by a mission at each time unit for the whole network lifetime. Sensors are moving according to Random WayPoint model (RWP). Thirty missions are uniformly distributed within the field. We assume that data packets are directly sent through GPRS data connection. Threshold based sensing scheme is used. We used two sensing thresholds (τ=25% and τ=50%). Also, we configured sensors to behave in *Naiive* fashion in which they sense all missions within their sensing range.

Our goal here is to test the effect of node density on utility received by missions from surrounding mobile sensors. Figure 5.2 shows the results we obtained. As expected, higher node density improves utility received by missions since each mission maybe sensed by more than one sensor. The *Naiive* sensing scheme outperforms the 25% or 50% thresholds based sensing schemes since it has no consideration of expected utility and missions can get benefit even from low utility values. As sensing threshold increase, quality requirements become higher and sensor needs to be more closer to sense a mission. This reduces number of times that a mission got sensed. This is reflected on the amount of utility it receives.

Using GPRS connection eliminate the effect of the deadline interval (T) on utility received by missions since all data packets are received with small delay. We found that there is no much effect on average utility each mission received when the number of missions is increased (with the assumption that sensors have

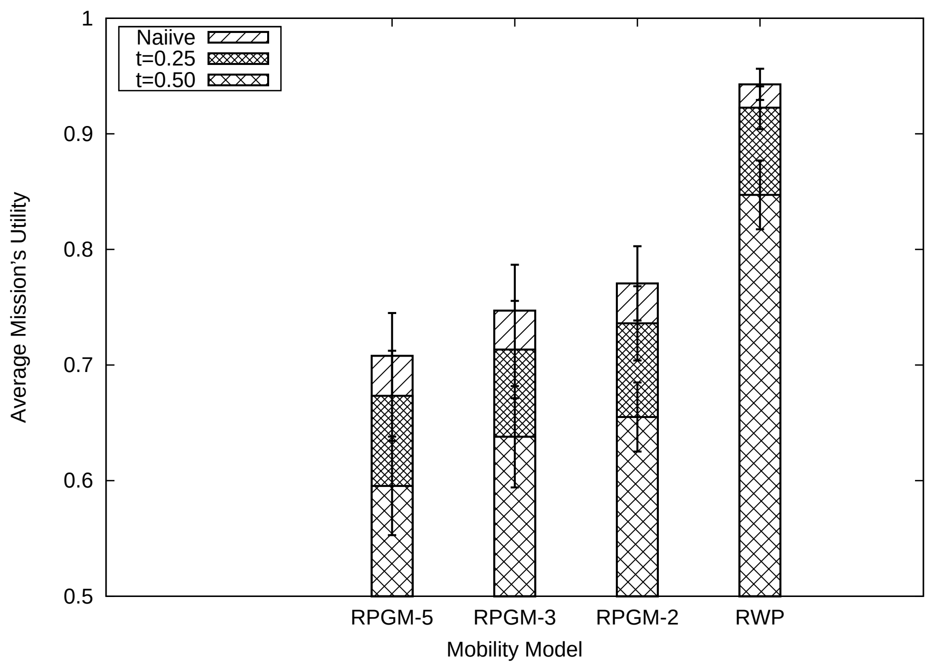


Figure 5.3: Average Mission Utility vs Mobility Model for 200 nodes with 30 Missions and GPRS data connection

enough energy supply). This happens due to the omni-directional operation of sensors. As we assumed earlier, a gas sensor reading can be used for detecting pollution level in an area with radius of its sensing range. Hence, all points (e.g. missions in our case) within that area are covered. This is not the case when sensors are directional, such as cameras, in which sensor can contribute only to the closest mission and other missions will receive zero utility even if they lie within the sensor's sensing range. Therefore, from here on, we show results only for 30 missions unless the number of missions makes a difference.

5.2.2 Utility vs Mobility

In the second set of experiments we study the effect of sensor node mobility behavior on the average utility received by a mission. Number of nodes set to

$N = 200$ nodes and the field has 30 missions that are uniformly distributed. Each sensor sends data directly through GPRS data connection. Sensors are moving according to RWP and RPGM models as in Table 5.1. In RPGM model, the number of nodes inside each group are varied (2, 3, and 5 nodes) within a maximum distance of 40 meters from group center and zero probability for a node to change its group to fix node density in each group. From Figure 5.3 we can see that RWP outperforms RPGM due to node grouping. As group members increases, the possibility that group members sense the same missions increase in which case redundant sensory data maybe received for a single mission. This improves utility for that mission, but on the other hand, other missions may not receive any utility which affects the overall performance. It becomes obvious when we decrease number of nodes within each group. Nodes grouping bounds the nodes ability to spread around to a larger geographic area which is reflected on coverage of the sparsely deployed missions near border areas. However, in RWP model, larger areas are covered and missions are likely to be covered better than in RPGM model since sensors move individually.

5.2.3 Utility vs Data Delivery

In this set of experiments we study the effect of data delivery mechanism on the average utility received by a mission. We use a network with 200 nodes with RWP model movement and data validity interval (deadline interval), T, equals 20 seconds. Data received after T seconds from its generation is useless

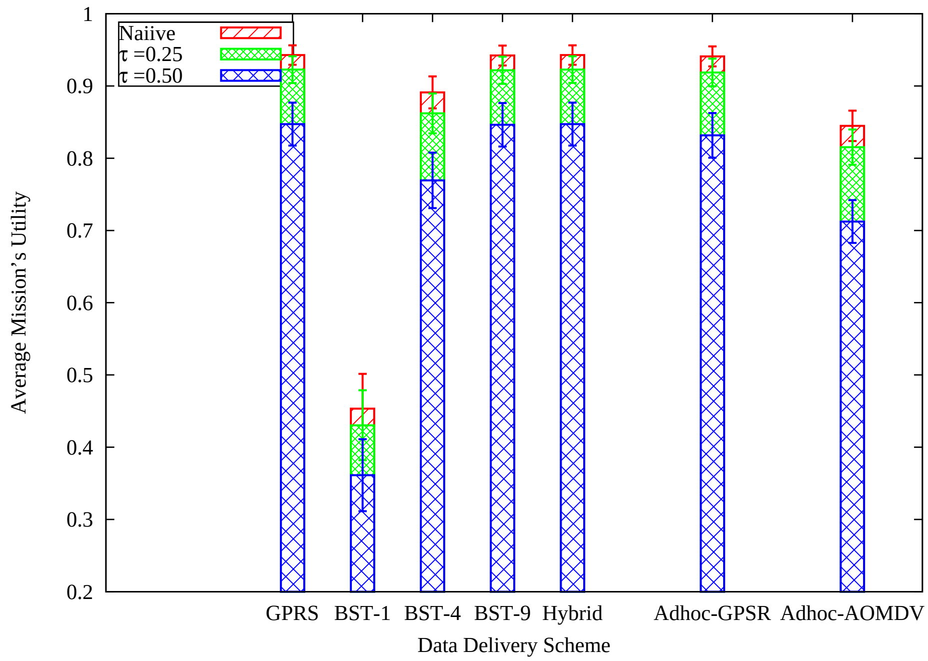


Figure 5.4: Average Mission Utility vs Data Delivery with 30 missions and 200 nodes. RWP model

and discarded by the application layer and from the sensor's buffer. We use different data delivery schemes as discussed in Section 4.2. In the case where sensor send only to open Wi-Fi access points (i.e. we call it here a base-station) it may coincidentally meet, we varied number of access points (1, 4, and 9 open access points or base-stations). We want to test the effect of Wi-Fi coverage on data delivery. When sensors use both GPRS and Wi-Fi communication modules (Hybrid approach), we use only one base-station in the center of network field. We also test ad-hoc delivery mechanism by using GPSR and AOMDV routing protocols for forwarding data packets to base-station node through the network formed between mobile sensors.

For GPSR we use original protocol implementation by protocol authors in [7] with same configuration except we here use only 1.5 second beacon interval.

We use AOMDV implementation available within *ns2* simulator [49] with a 1.5 second HELLO interval. Sensor node setting (sensing, communication and energy consumption settings) was set as in Table 3.1. Figure 5.4 shows the results of the experiments.

GPRS connection provides best coverage since data are directly sent to base-station which reflected on average received utility by each mission where no data packets are discarded. However with Wi-Fi only, when there is only one base-station, about 12% of field area are covered, delayed data packets are discarded which reduces amount of sensory data received by each mission as it appear in Figure 5.4 (more than 50% of mission's utility is lost). By increasing number of base-stations in the field, there is a higher possibility that sensors find open access points to send data to back end servers. Even when four base-stations are used, a small amount of data packets are discarded from sensor buffer due delay. When the number of base-stations is increased to 9, all field areas are covered (we assume a grid based base-station positioning such as 2X2 or 3X3) and sensor data are directly sent to one of these base-stations. This improves received utility by each mission to reach levels similar to GPRS. In real world scenarios, full coverage of Wi-Fi access points is not always available. However, we add it here to test the effect of communication coverage in data delivery and received utility as it appear in Figure 5.4 in which the addition of more than 9 base-stations is useless since all the field is covered.

As we expect, hybrid approach behave similarly to GPRS connection. In hybrid approach, GPRS is always used in the absence of a base-station. Therefore, all data packets are delivered either using Wi-Fi access point (when available), or using GPRS connection.

Almost all data packets are delivered when sensors use ad-hoc network and GPSR as a routing protocol which reflected on average utility received by each mission (almost similar to GPRS connection and Hybrid approach) which was really surprising at the beginning. We found, however, that GPSR was doing well at high node density since we used 200 sensors which make an average network diameter of about 25 neighbors for each mobile sensor. This ensures that GPSR source node always find a neighbor to forward its data packet to the base-station. In case of MAC layer failure (node could not send or forward packet due to collision), the GPSR protocol uses a technique, to increase delivery ratio, by handling packets at network interface destined to failed hop to the routing layer (GPSR routing protocol) to be re-forwarded again. Therefore, each packet gets another chance to be forwarded to a next hop toward destination.

With the AOMDV routing protocol, not all sent data packets are delivered to base-station node which is reflected on the utility received by each mission. This is due to the reactive mechanism AOMDV uses (as discussed in Chapter 4) in which it starts route discovery (find multiple paths toward destination) only when traffic starts or when available routes fail. Therefore, packets are dropped when there is no route found. GPSR, on the other hands, works in a proactive fashion (i.e. before any traffic) in which each node builds it owns neighbors table

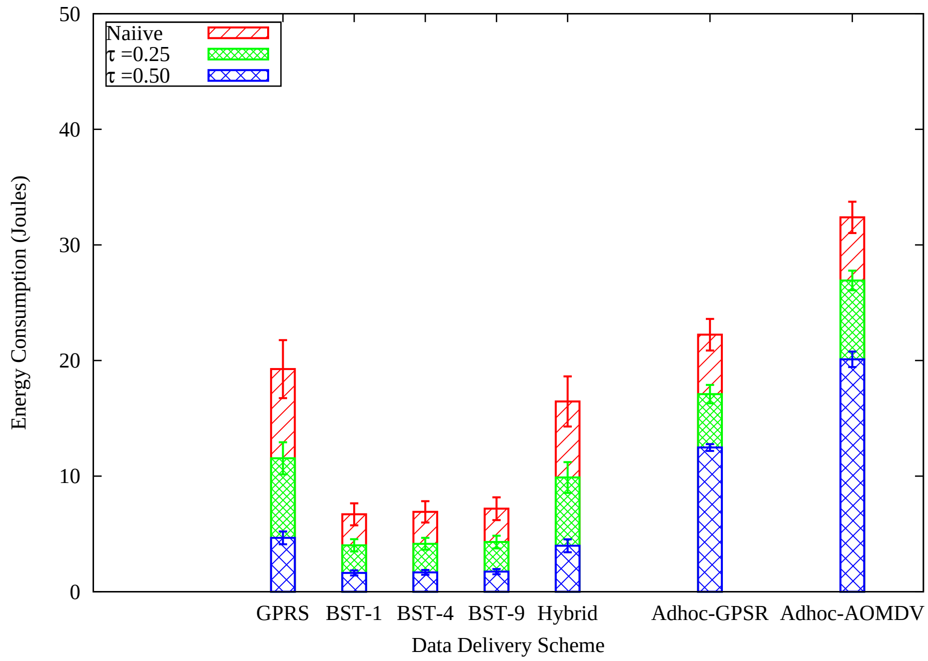


Figure 5.5: Average Node Energy Consumption vs Data Delivery. with 10 Missions and 200 nodes, RWP model

that will be used to forwards data packets. Therefore, GPSR performs better in data delivery compared to AOMDV that consume more time and bandwidth to find destination node.

5.2.4 Energy Consumption vs Data Delivery

In this set of experiments, we show the effect of data delivery scheme on the average energy consumed by each node. Sensor consumes energy only for sensing and communication operations (transmition and reception) as specified in Table 3.1. Different number of missions (10, 20, and 30) are uniformly distributed within the field. In general, without considering delivery scheme, energy consumption should increase when we increase the number of missions. This is expected as sensors spend more time in sensing and transmitting generated measurements to

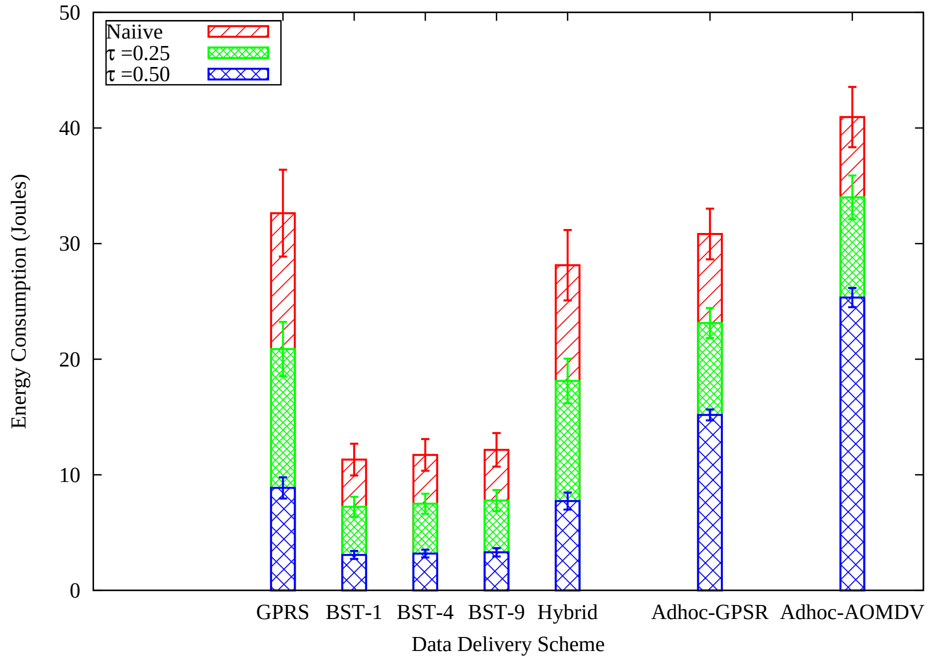


Figure 5.6: Average Node Energy Consumption vs Data Delivery. with 20 Missions and 200 nodes, RWP model

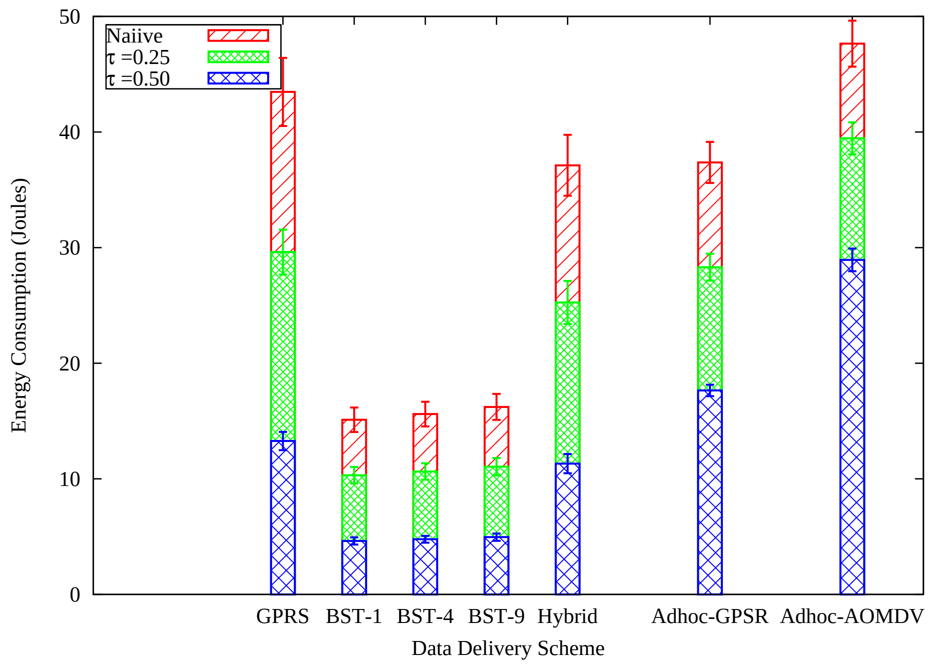


Figure 5.7: Average Node Energy Consumption vs Data Delivery. with 30 Missions and 200 nodes, RWP model

base-station. This becomes clear when the threshold, τ, is decreased and energy consumption reaches its maximum when sensors become *Naiive* as can be seen in Figures 5.5, 5.6, 5.7. Sensors consume the least energy when they only use Wi-Fi for sending data packets. There is a little increase when more base-stations are used. This is expected since sensors send more packets when nine base-stations are used than when only one or four base-stations are used. However, we found that sensors consume a large amount of energy due to overhearing other nodes transmitted packets. This is mandatory since sensor need to keep its Wi-Fi module open to be able to find open access points.

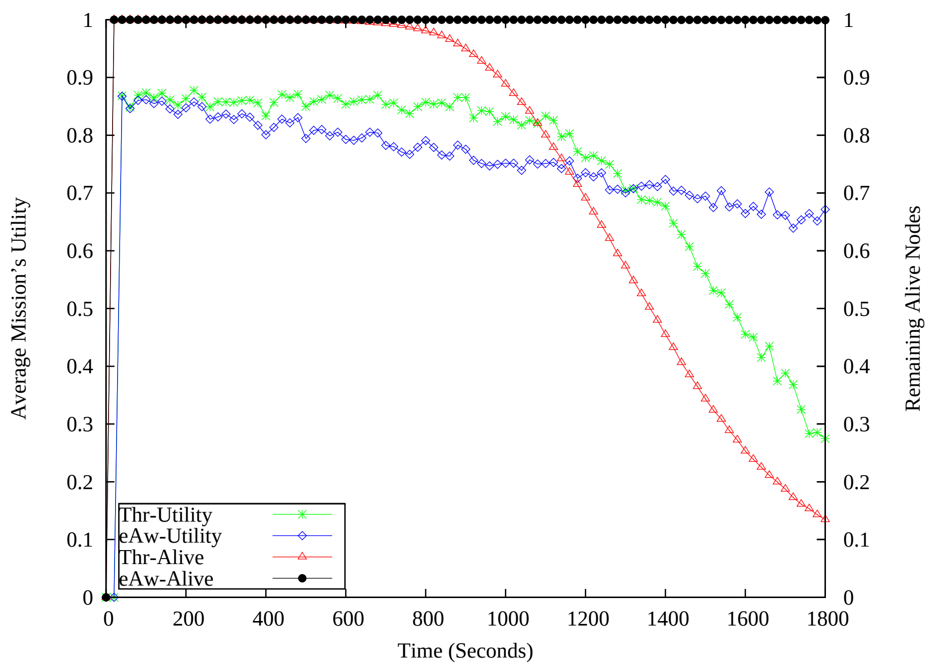
GPSR and AOMDV routing protocols have the highest energy consumption, even higher than GPRS connection. This is due to the fact that in both protocols, a sensor performs a routing role beside its sensing task. According to our assumption, when GPRS is used, nodes do not affect each other while transmitting which is not the case in ad-hoc communication. Also, GPSR uses periodic beacons (even when there is no packets to send) to keep the neighbor's table fresh which consumes more energy for both transmition and reception of these beacons by sensors. AOMDV consumes more energy than GPSR routing protocol due its route discovery process (route request messages are broadcasted network wide). Also, AOMDV use periodic HELLO messages to detect link failure which consumes energy. Although GPSR uses explicit periodic beaconing, it uses sent packets as implicit beacons which reduces number of sent beacons by each node as more data packets sent or forwarded.

When data packets are delivered using a GPRS connection, energy consumption was high due to high current levels (1.4A) when sensor communicates with network carrier for data transmition. However, when a sensor uses both Wi-Fi and GPRS modules simultaneously, energy consumption decreases since the Wi-Fi module consume less current than in GPRS module as in Figures 5.5, 5.6, 5.7.

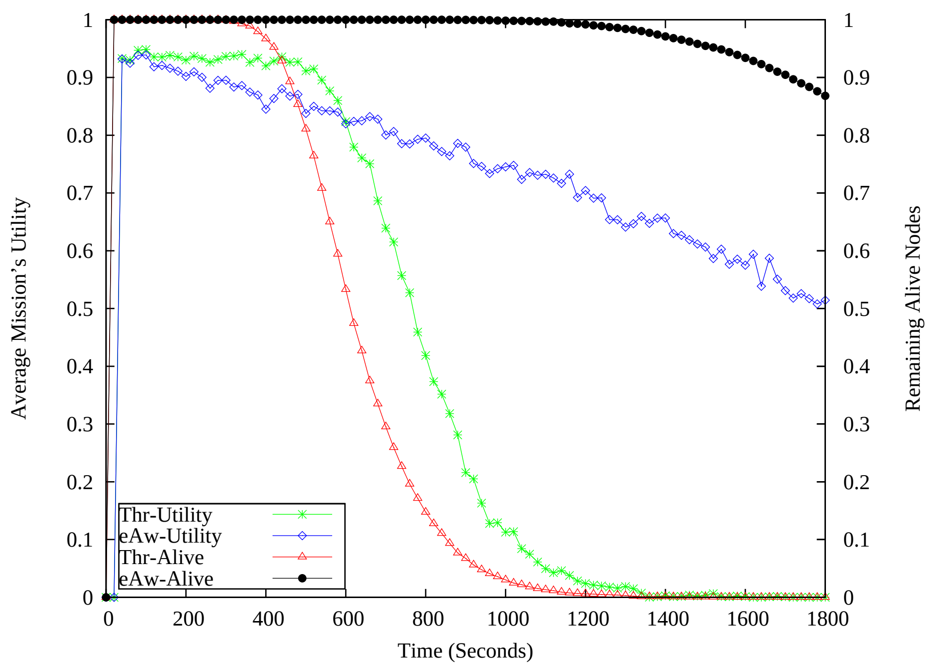
5.2.5 Threshold-Based vs Energy-Aware Sensing

In the previous experiments, we used threshold based sensing in which the expected utility e_{ij} must be greater than a predefined threshold to start the sensing module. In this set of experiments we show time trace compare threshold based and energy aware sensing schemes using the previously discussed data delivery schemes. As explained in Section 4.1.2, energy aware scheme adapts sensing threshold according to fraction of sensor remaining energy as in equation 4.1. We consider average utility received by each mission, and percentage of alive sensor nodes during network life time as our metrics. We used 200 nodes, each configured with 10 Joules as battery capacity that will be used for both sensing and communication tasks. Sensors move according to RWP mobility model. Thirty mission are uniformly distributed within the network field. Network life time set to 1800 seconds but sensor start sensing after 20 seconds to allow the steady state. Sensors initially configured with two different sensing thresholds, τ=0.50 (50%) and τ=0.25 (25%).

In Figure 5.8, sensors directly send sensory data through a GPRS connection.



(a) τ=0.50



(b) τ=0.25

Figure 5.8: Energy-Aware vs Threshold-Based Sensing schemes. Time trace for 30 Missions and 200 nodes, GPRS connection

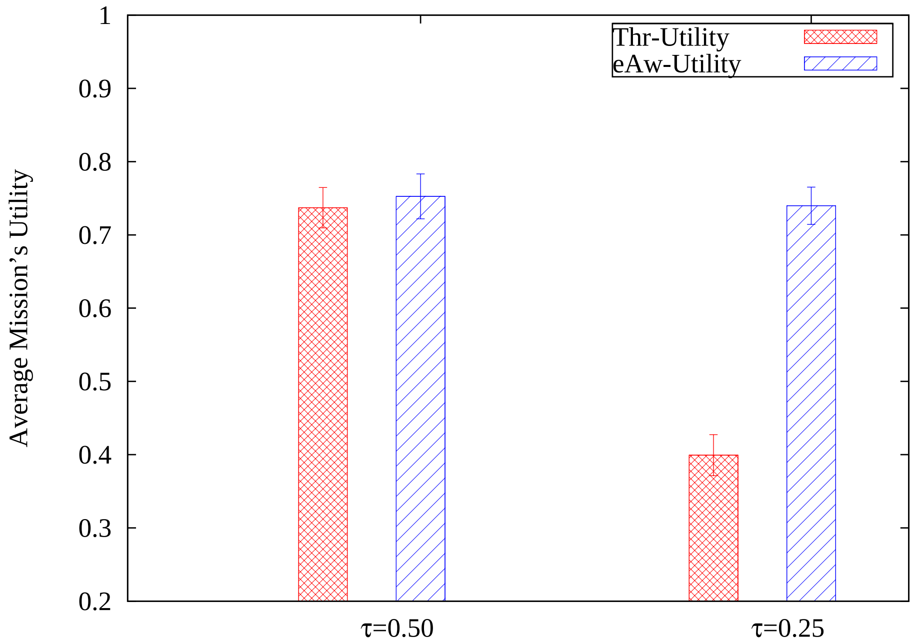
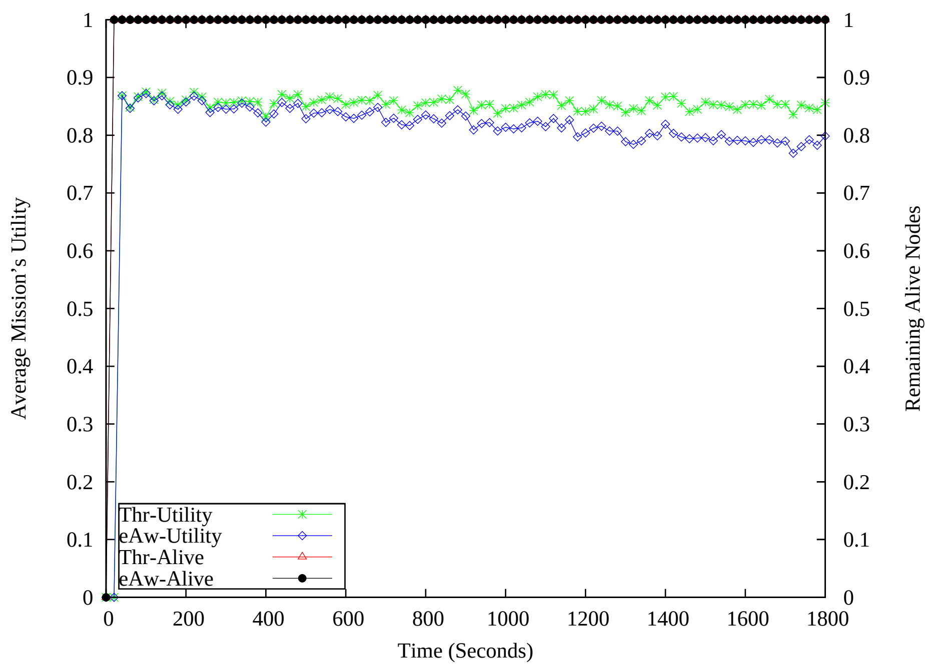


Figure 5.9: Energy-Aware vs Threshold-Based Sensing schemes. Average Mission's utility with 30 Missions and 200 nodes, GPRS connection.

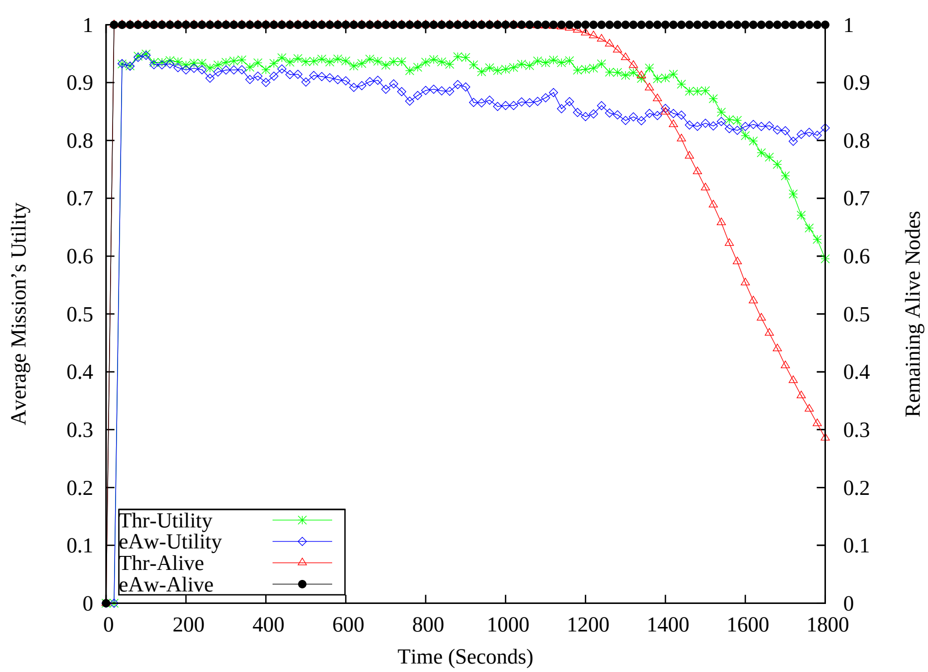
As we can see, with threshold based sensing scheme, the average number of alive network nodes decrease drastically. This happen because sensors only consider utility and not the remaining energy which draws its battery. This becomes clear when we decrease utility requirement by using a smaller thresholds as in Figure 5.8b. When sensor has no more energy it can not sense or send any data which is reflected on the utility received by missions as more nodes die as in Figure 5.8a. In Figure 5.8b, all nodes die by the end of simulation time and the average utility level reaches zero since there are no more alive sensors to serve the missions. However, with energy aware scheme, sensors take energy levels into account before contributing to a mission (i.e. sense mission). From Figure 5.8, in energy aware sensing, sensors start similar to the threshold based sensing scheme. However, when more energy is consumed, sensors become more conservative by increasing its sensing threshold (see Equation 4.1). Therefore, only missions with high utility expectations are sensed. This strategy reduces energy spent on less useful missions when battery level are low which extends network lifetime even when small thresholds are used as in Figures 5.8a, 5.8b. Figure 5.9 shows average of utility received by each mission through the whole network lifetime. It is clear that energy-aware performs better than threshold based sensing when low threshold is used. Threshold based, on the other hand, does well with high threshold, (τ=50%, almost similar to energy aware).

In Figures 5.10 and 5.11, we only use Wi-Fi communication module for sending data with 9 base-stations. We used this number of base-stations to provide full connectivity. We can see in Figure 5.10a that with high threshold (τ=50%), sensor doing better than when energy aware is used. This happen because nodes are configured with more than enough energy. However, the energy-aware scheme tries to save energy which caused little degradation in received utility. When small threshold is used (τ=25%), we see a degradation in received utility for the threshold-based scheme after 1600 seconds of simulation time and almost 50% of sensors are dead. This clearly appears in Figure 5.11 where threshold based sensing outperforms energy aware in average utility received by each mission during the network lifetime. However, energy aware saves nodes energy than when only threshold sensing scheme is used (all nodes still alive when τ=25% is used and only about 50% for the threshold-based by the end of simulation time).

In Figures 5.12 and 5.13, sensor uses both communication modules (Wi-Fi



(a) τ=0.50



(b) τ=0.25

Figure 5.10: Energy-Aware vs Threshold-Based Sensing schemes. Time trace for 30 Missions and 200 nodes, 9 Base-stations

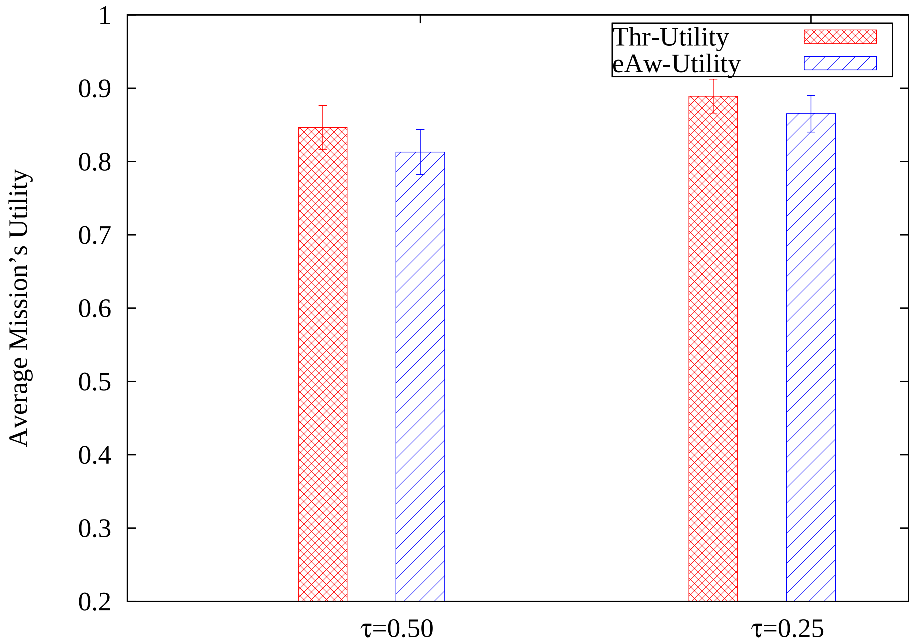
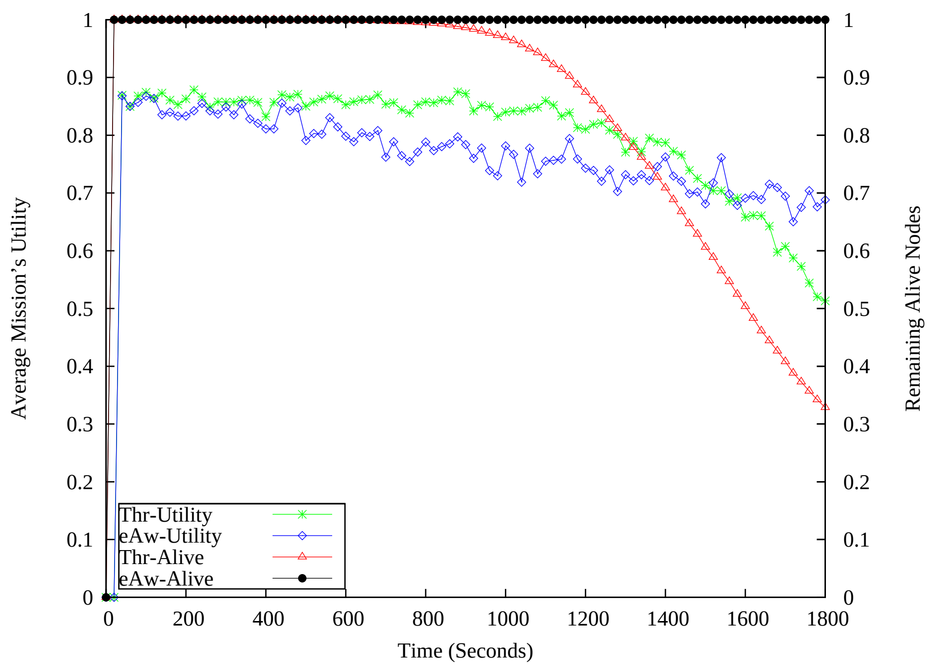


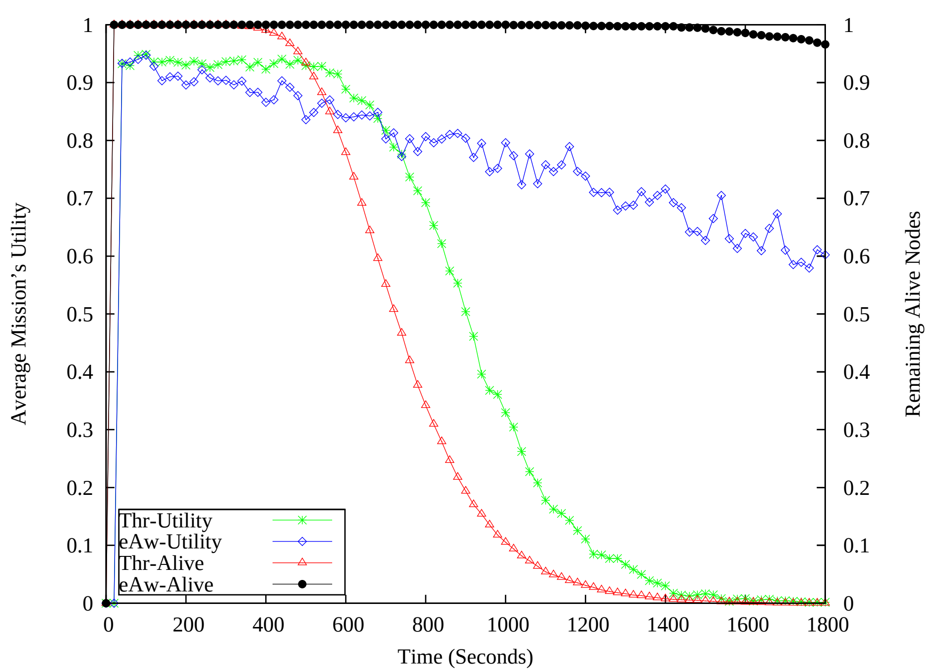
Figure 5.11: Energy-Aware vs Threshold-Based Sensing schemes. Average Mission's utility with 30 Missions and 200 nodes, 9 Base-stations.

and GPRS) interchangeably for data packets transmition. The addition of Wi-Fi module (hybrid approach) improved usage of node battery. By the end of simulation time, percentage of remaining alive nodes in the hybrid approach was about 30% as in Figure 5.12a. However, when only GPRS connection is used, alive nodes was almost 13% as in Figure 5.8a.

In Figure 5.12, at the beginning, threshold based scheme performs better than energy aware since it has no consideration to energy levels. Therefore, number of alive node decrease drastically because energy is drawn quickly as in Figures 5.12a and 5.12a. On the other hand, the energy aware scheme depends on spending energy only for valuable missions by increasing its sensing threshold. This strategy helps in extending network lifetime and at the end of the simulation, as almost 95% of nodes still alive as in Figure 5.12b. This is reflected on the average utility



(a) τ=0.50



(b) τ=0.25

Figure 5.12: Energy-Aware vs Threshold-Based Sensing schemes. Time trace for 30 Missions and 200 nodes, Hybrid (Wi-Fi and GPRS connection)

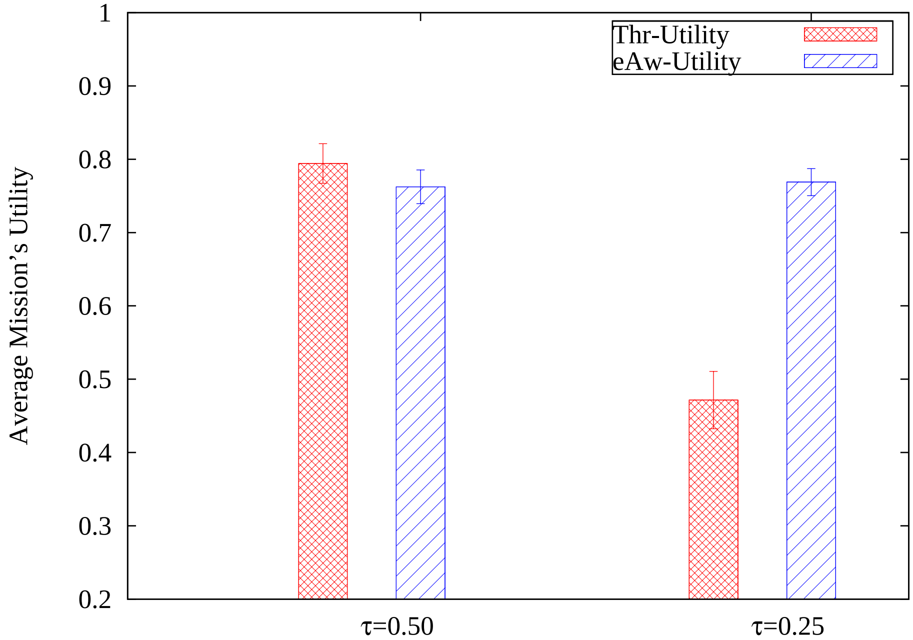
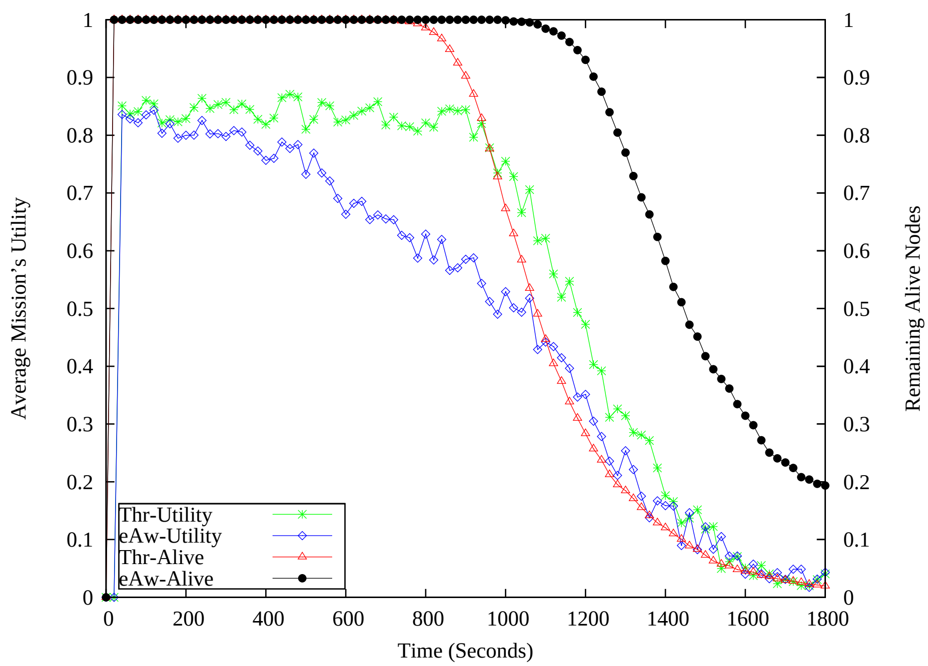


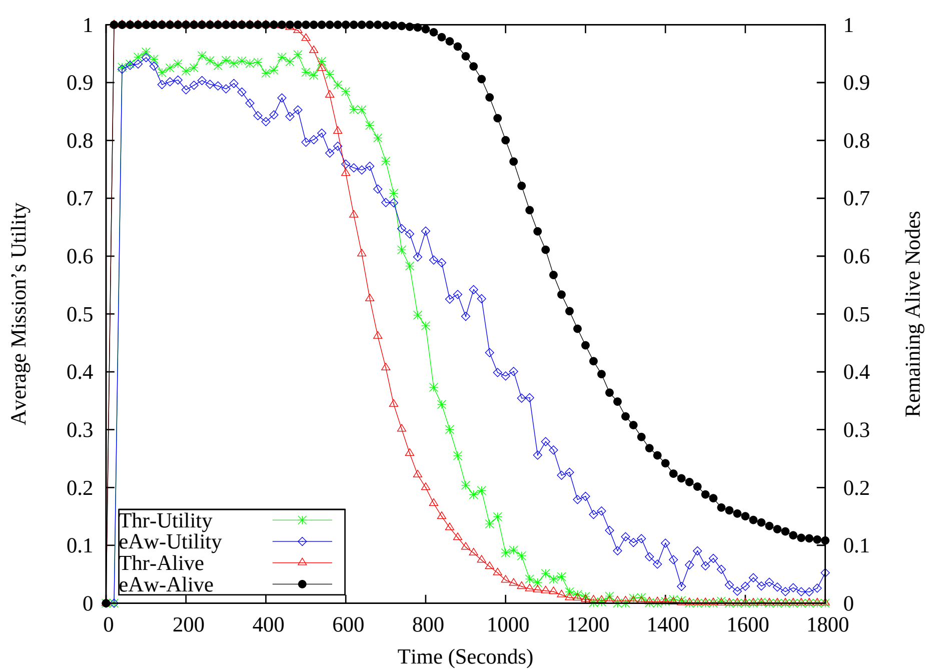
Figure 5.13: Energy-Aware vs Threshold-Based Sensing schemes. Average Mission's utility with 30 Missions and 200 nodes, Hybrid (Wi-Fi and GPRS connection).

received by mission through the network life time as in Figure 5.13. Although energy aware saves more energy, its performance was little bit less than when high sensing thresholds is used (50%). When small threshold is used (25%), energy aware performs better since it spends energy only for higher utility missions.

In Figures 5.14 and 5.15, sensors form an ad-hoc network between them to forward data using GPSR routing protocol to base-station. Unlike previous experiments, both threshold and energy aware perform badly. In the previous experiments, energy is only consumed to sense missions and send generated measurements to base-station. GPSR protocol works in a proactive fashion where every sensor send a periodic beacon to its one-hop neighbors. This consumes more energy since sensors send and receives others beacons. Although that energy aware



(a) τ=0.50



(b) τ=0.25

Figure 5.14: Energy-Aware vs Threshold-Based Sensing schemes. Time trace for 30 Missions and 200 nodes, GPSR routing protocol

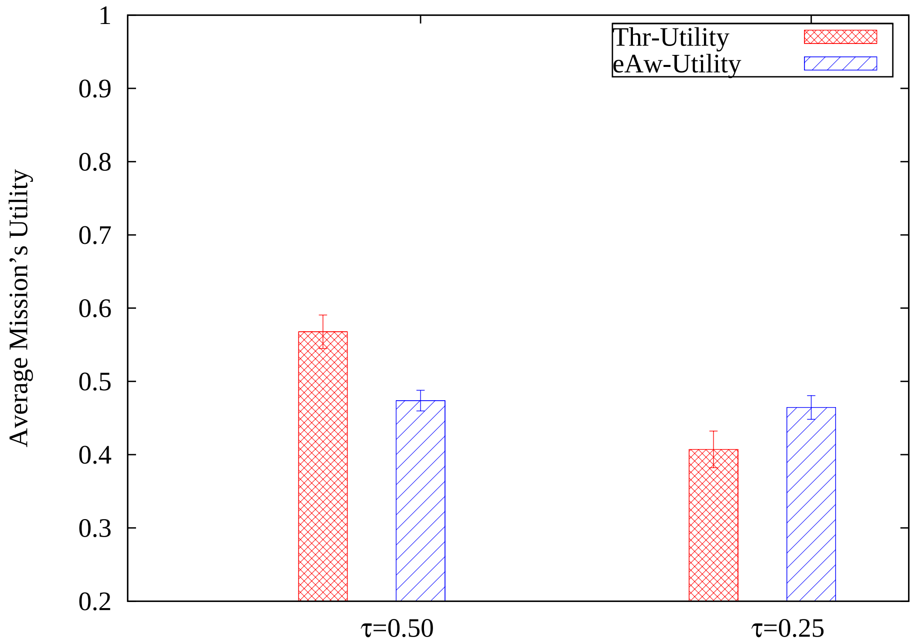
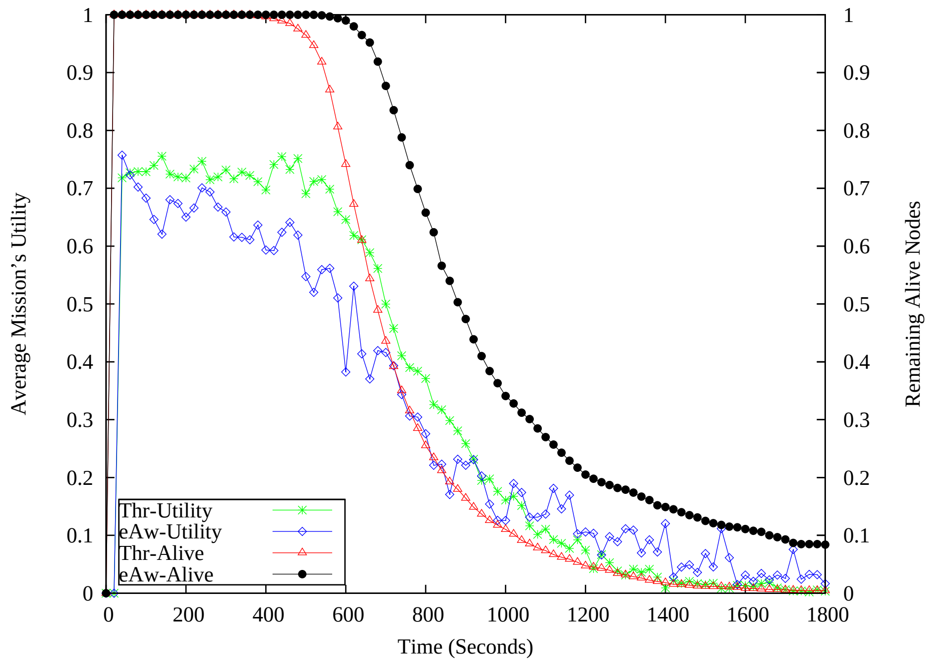


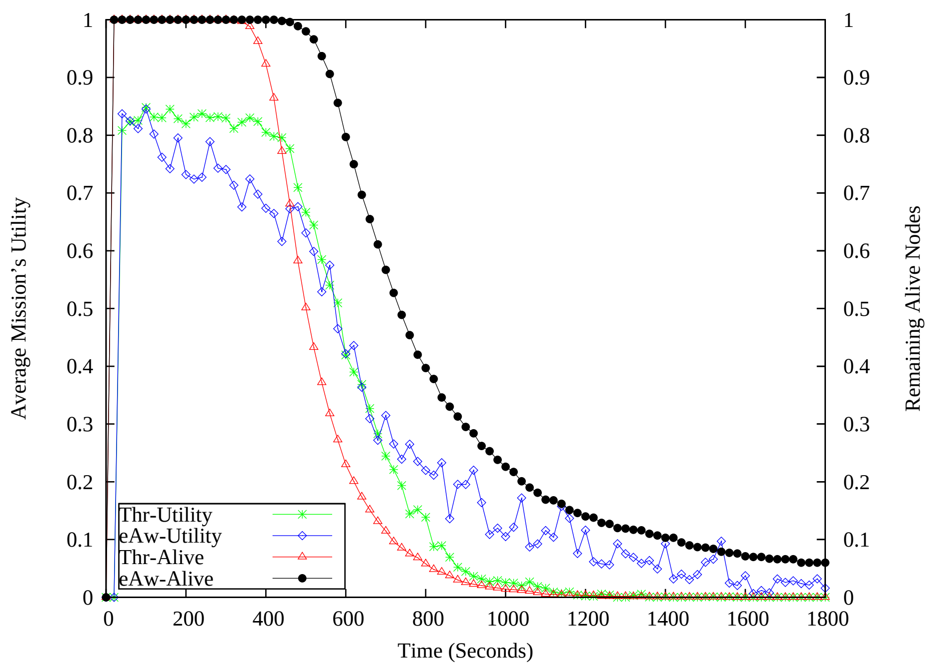
Figure 5.15: Energy-Aware vs Threshold-Based Sensing schemes. Average Mission's utility with 30 Missions and 200 nodes, GPSR routing protocol.

when $\tau = 0.25$ performs better than the non-energy aware schemes, we can say that there is no real control on energy leakage by the sensing scheme.

Figures 5.16 and 5.17 shows performance of AOMDV using both threshold and energy aware sensing schemes. AOMDV performs worse than GPSR routing protocol. Because AOMDV broadcast many route request packets in the discovery process, energy is consumed faster than in GPSR even when high threshold is used. This is also because AOMDV starts sending HELLO messages (every 1.5 second) for link failure detection after the route discovery process starts. This is reflected on average utility received by each mission. Although energy aware tries to save battery by reducing the number of times it sense missions, energy leaked due to the routing protocol's behavior downgrade network performance quickly and more nodes die faster than with GPSR as we can see in Figure 5.17.



(a) τ=0.50



(b) τ=0.25

Figure 5.16: Energy-Aware vs Threshold-Based Sensing schemes. Time trace for 30 Missions and 200 nodes, AOMDV routing protocol

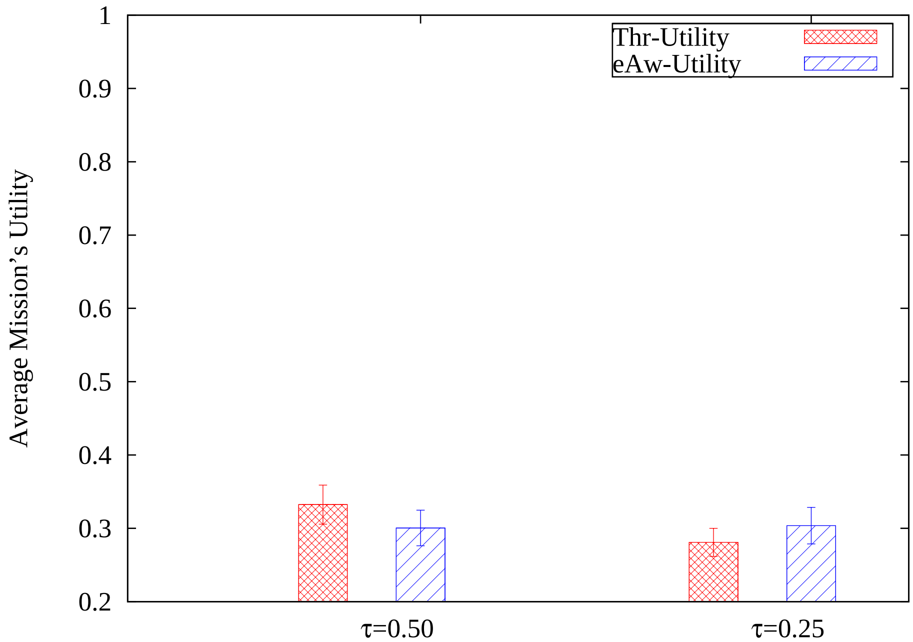


Figure 5.17: Energy-Aware vs Threshold-Based Sensing schemes. Average Mission's utility with 30 Missions and 200 nodes, AOMDV routing protocol.

In next chapter we go into further details for using GPSR and AOMDV routing protocols on top of MWSNs.

5.2.6 Discussion

In general, we can say that energy aware scheme works similarly to threshold based sensing when the fraction of remaining energy is high. However, when energy decreases it reacts by increasing sensing thresholds. Even this extend network lifetime, however, it may affects utility received by missions due to sensors become more selective to sense missions with high utility expectation.

Most of existing routing protocol in wireless sensor networks designed for statically deployed sensors. Instead, we used two MANET routing protocols, GPSR and AOMDV. GPSR performs better than AOMDV due to its advantage of using geographic information which cuts the need for expensive route discovery process. However, the proactive nature used by both protocols affects their performance due to energy limitation.

CHAPTER 6

EVALUATION OF GPSR AND AOMDV ROUTING PROTOCOLS FOR MWSNS

In Chapter 5, we used GPSR and AOMDV routing protocols to deliver data packets to base-station node through an ad-hoc network formed between sensors. In this chapter we go further by testing performance of both protocols for MWSNs using different set of experiments.

6.1 Simulation Setup

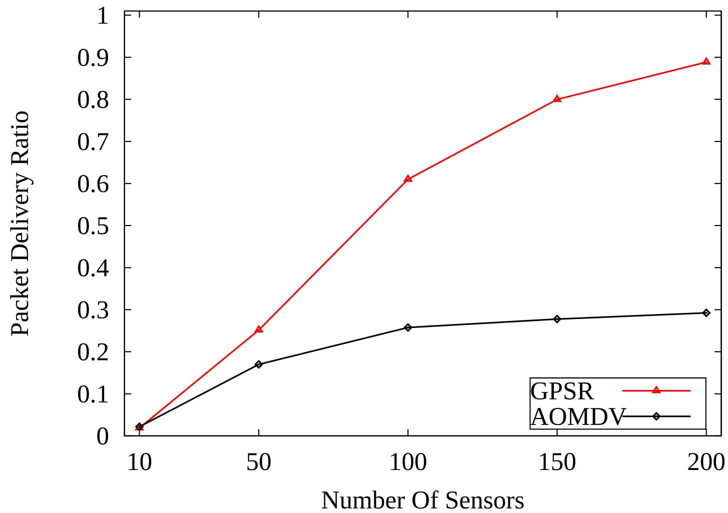
We used similar settings as used in Section 5.1. All missions are modeled as event detection missions such as chemical leakage or fire detection for alarm monitoring systems. We used 30 missions uniformly distributed within (400 X 400) square meters field. We assume that sensor is *Naiive* in which it has no consideration of expected utility contribution and senses every mission within its range even if e_{ij} is too small. Mobile sensors move according to Random Way Point (RWP) [38] model as in Table 5.1. We run set of experiments for evaluating GPSR and AOMDV routing protocols. We used a 1.5 seconds interval for both GPSR 's beacons and AOMDV 's HELLO messages. Obtained results are taken based on network lifetime of 1800 seconds and averaged over 20 runs.

6.2 Results and Discussion

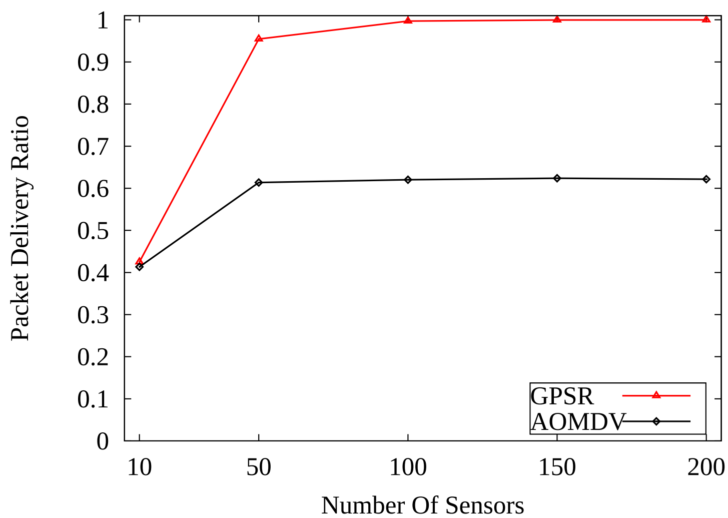
In the following experiments runs, we vary node density from 10 to 200. We place the base-station at different locations in the field (corner and center). We evaluate the routing protocol (both GPSR and AOMDV) performance according to five different metrics, packet delivery ratio, utility received by each mission, routing protocol overhead, hop count and the node energy consumption.

6.2.1 Packet Delivery Ratio

Figure 6.1 shows the percentage of successfully delivered data packets to the base-station. We can see that both routing protocol performs similarly when low density is used (only 10 nodes) because the network is disconnected most of the time. However, when more nodes are used both protocols perform better since the probability of finding a path or next hop toward destination increases (higher network diameter). GPSR performs better than AOMDV routing protocol be-



(a) Base-station is positioned at the corner of the field.

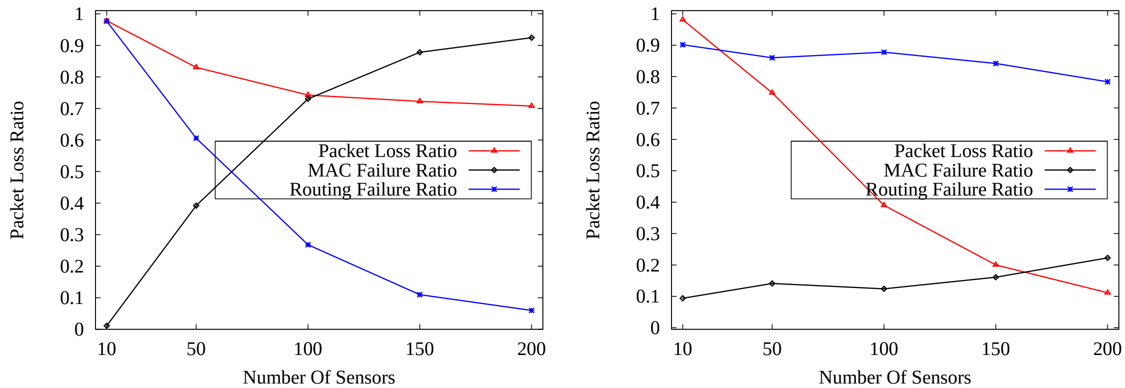


(b) Base-station is positioned at the center of the field.

Figure 6.1: Packet Delivery Ratio

cause AOMDV consumes a lot of time and network bandwidth in finding a path towards the destination by broadcasting request messages. In GPSR, nodes know their locations, their neighbors' locations and the location of the destination which helps in finding the shortest path to destination. Also, GPSR works in a proactive fashion in which each node has a list of its current neighbors before any traffic starts.

Location of base-station, as expected, plays a major role in data delivery. When the base-station is positioned at the corner of the field (worst case), both protocols perform badly when low node density is used (only about 1% of generated data packets are delivered, as can be seen in Figure 6.1a). The farther the base-station is located, the possibility that packets are dropped by intermediate nodes increases because there is no valid path to destination. This is especially true when low density is used. GPSR performs better than AOMDV when more nodes are deployed. GPSR has the advantage of leveraging the higher node density because the source node uses geographic information to find the shortest path possible to the destination node. When the base-station is positioned at the center, almost all packets are delivered when more than 100 nodes are deployed, (see Figure 6.1b). We notice that AOMDV is saturated when network density is increased in which only about 20-30% of all sent packets are delivered in worst case, i.e. when base-station at corner, (see Figure 6.1a), and almost 60% of sent packets are delivered in the best case when base-station is at the center of the field (Figure 6.1b).

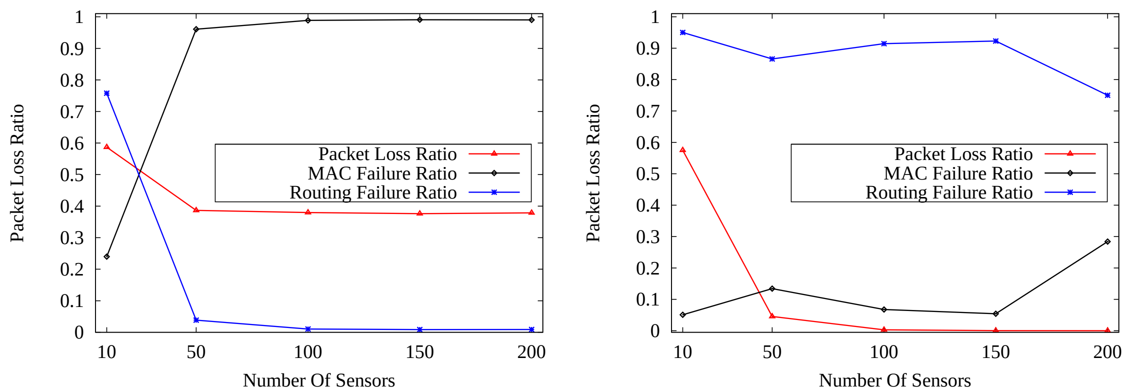


(a) AOMDV (b) GPSR

Figure 6.2: Packet Loss Ratio, base-station is positioned at the corner of the field.

Figures 6.2 and 6.3 show the ratio of lost data packets and the effect of both Routing and MAC layers failure on the packet loss ratio (PLR). We show this for both cases in which base-station is positioned at corner and center of the field respectively. Both Routing and MAC failure are ratios to the number of lost packets which reveals the responsibility of each layer which caused packets to be dropped.

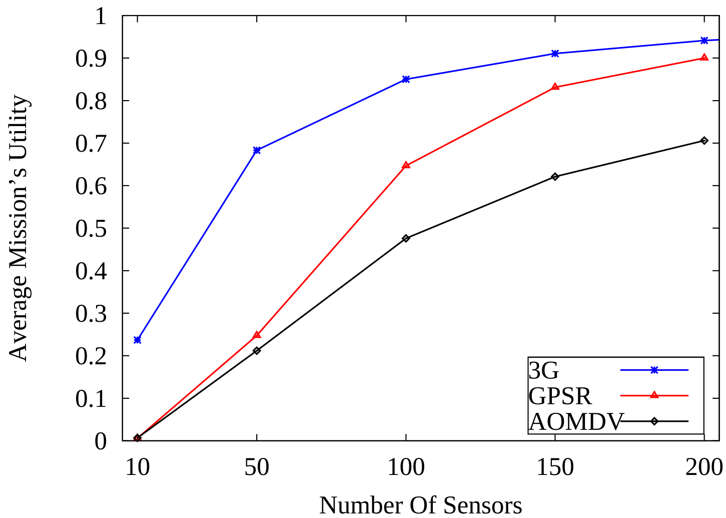
MAC failure happens when packets are dropped because the MAC layer could not send a packet to the next hop either because it has already left the communication range or because of collision. Routing failure happens when the source or the forwarding node could not find a valid route towards the destination (sometimes packets are dropped due to loop in the path). We can notice that most of the packets are dropped due to route failure when low network density is used. This becomes clear when the base-station is positioned at the corner of the field. In this case, the base-station and network nodes are disconnected most of the time.



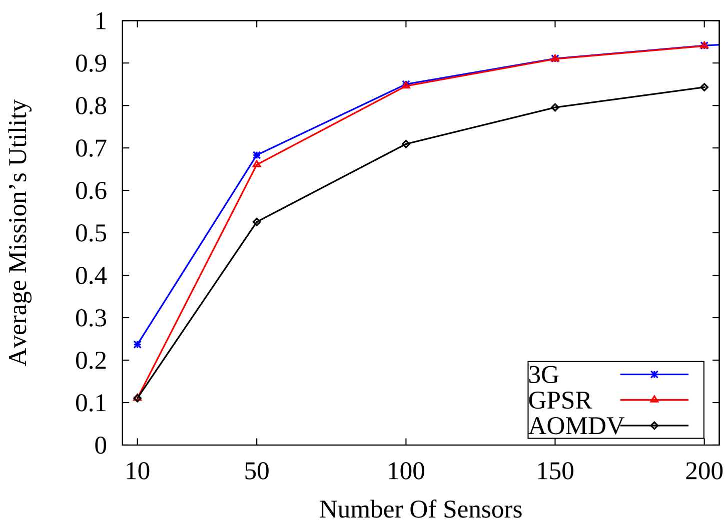
(a) AOMDV (b) GPSR

Figure 6.3: Packet Loss Ratio, base-station is positioned at the center of the field.

In AOMDV, we can see that most of the packets are dropped because of Mac failure. This happens because of packets collision especially when node density is increased (more than 50 nodes) due to the high number of sent routing control packets during the route discovery and maintenance process, (see Figures 6.3a and 6.2a). In GPSR, effect of Mac failure is limited since GPSR sends only one-hop beacons which is not the case in AOMDV (i.e. AOMDV broadcast a route request message network wide to find destination). Also, GPSR uses sent data packets as implicit beacons which decreases the number of sent beacons. Although the data packet loss ratio decreases as more nodes deployed (few packets is dropped), most of the dropped packets in GPSR are due to routing protocol failure which is acceptable since GPSR depends on sent beacons to make routing decision, (see Figures 6.2b and 6.3b).



(a) Base-station is positioned at the corner of the field.

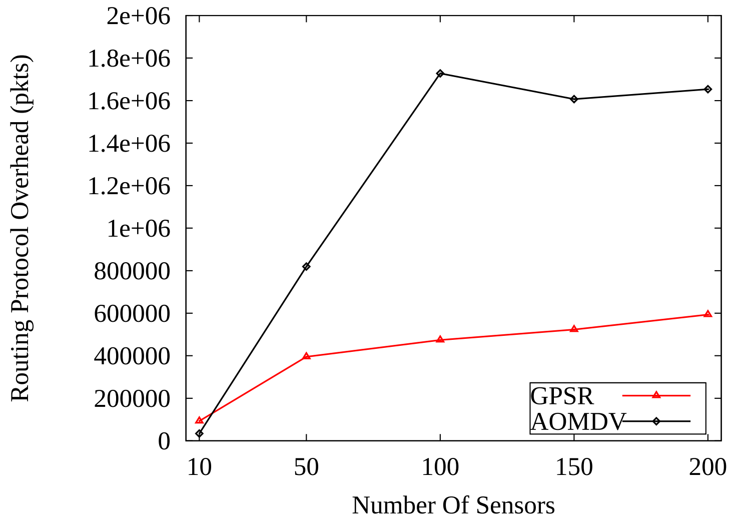


(b) Base-station is positioned at the center of the field.

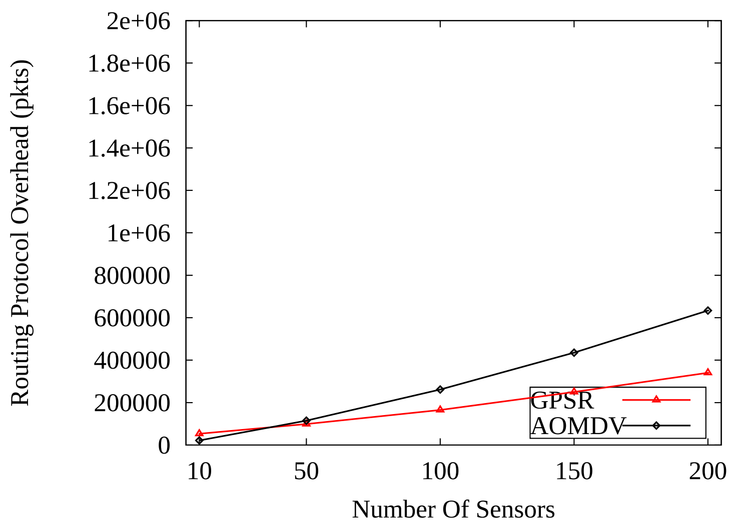
Figure 6.4: Average Mission's Utility, 30 missions.

6.2.2 Mission's Received Utility

Each network mission receives utility based on measurements taken by network mobile sensors. We used this metric to see effect of the underlying data delivery (routing protocol) mechanism on application performance. We also run same experiments in which sensor sends data packets directly using GPRS connection (we call it 3G in figures) as used in [22],[3],[25]. Figure 6.4 shows the average utility received by each mission during the whole network life time (we calculate the utility as described in Chapter 5). As expected, higher node density improves application performance (event detection probability) since more missions are covered when more sensors are deployed (specially when 3G connection is used). The effect of packet delivery ratio (see Figure 6.1 and Figure 6.4) is reflected on the application performance. GPSR outperforms AOMDV when higher node density is used due to its high packet delivery ratio especially when the base-station is positioned at the field center (Figure 6.1b). When base-station at the field center, GPSR behaves similar to 3G connection when more than 50 sensors are used (see Figure 6.4b). We can also see that the performance of AOMDV is not bad even when it delivers only 62% of the generated measurements (Figure 6.1b). This is because not all measurements contain high quality information as we assume that sensors are *Naiive*, and sometimes these measurements are for the same mission.



(a) Base-station is positioned at the corner of the field.



(b) Base-station is positioned at the center of the field.

Figure 6.5: Routing protocol overhead. All routing packets sent network wide.

6.2.3 Routing Overhead

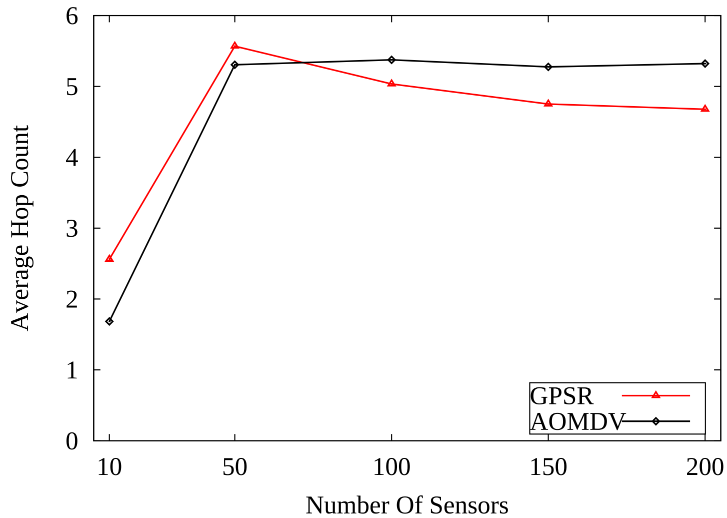
Figure 6.5 shows the routing protocol overhead defined as all sent routing packets during the whole network life time which is 1800 seconds. Routing overhead include routing packets initially sent by source node, forwarded packets, and all routing control messages sent by each node (beacon, request, reply, error, and hello messages). As expected, AOMDV produces much high overhead compared to GPSR in the route discovery process (request, reply, and error messages). Also, AOMDV uses HELLO messages for broken link detection which increases the protocol overhead. GPSR, on the other hand, uses only location information for packet forwarding and it does not need any route discovery. Also, GPSR allows the routing protocol to exploit sent packets as implicit beacons which reduces the need to send more beacons. Position of the base-station affects the performance of both routing protocols. When the base-station is at the corner of the field, both protocols need to send more packets for data delivery. AOMDV is drastically affected by location of base-station since all sensors want to send packets to base-station which initialize a route discovery process by all network nodes (due to the all to one nature of traffic in MWSNs). We can see that effect when node density is increased (see Figure 6.5a). When the base-station is at the center of the field, distance between source and destination is smaller and paths are formed faster and with less overhead (see Figure 6.5b). Although that GPSR does not need route discovery, packets need to follow a longer paths when base-station is at the corner than when it was positioned at the center which increases the overhead produced by the routing protocol.

6.2.4 Hop Count

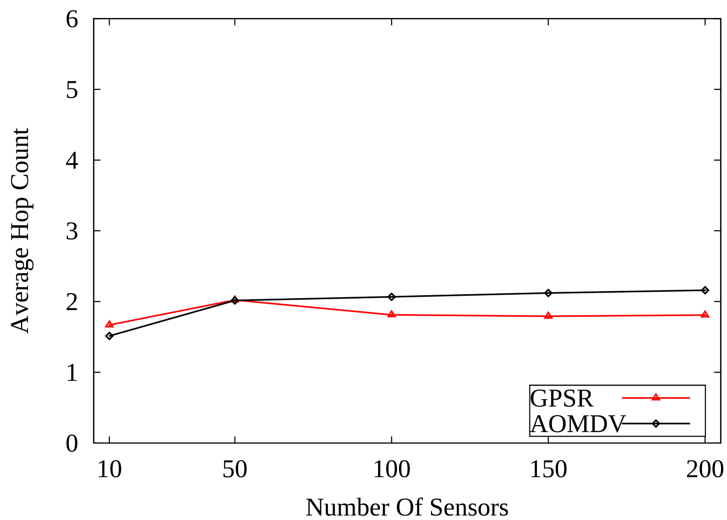
Figure 6.6 shows average hop count that received packets traverse before they reach the base-station. We only consider number of hops between source node and destination as it reflects the path length and the ability of the routing protocol to find and use the shortest path. As expected, the farther the base-station was positioned, the longer the path packets follow before they are successfully delivered (see Figure 6.6a and Figure 6.6b). In GPSR, we can see that packets, when node density is low (10 nodes), follow a longer path than AOMDV. This is because when greedy forwarding fails, GPSR tries to forward the packets around void areas using perimeter mode. This means that packets traverse along more nodes with the hope to find destination. However, when more nodes are deployed, network diameter increases and GPSR choose to forward packets to the closest hop to destination (more neighbors to choose from). This is reflected on the path length used by GPSR as it becomes shorter than AOMDV 's which uses existing route unless it fails, then it tries to use an alternative one.

6.2.5 Energy Consumption

Figure 6.7 shows the average energy consumed by each sensor during the whole network life time. Sensors consume energy for both sensing and communication as specified in Table 3.1. Since nodes behave similarly in the sensing operation,

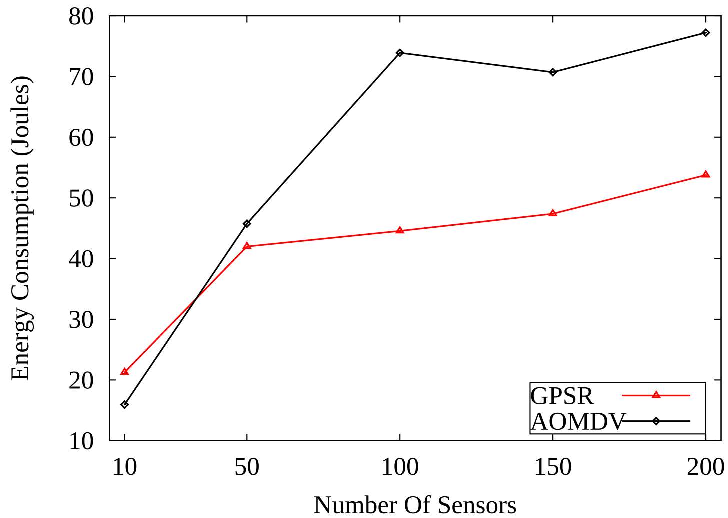


(a) Base-station is positioned at the corner of the field.

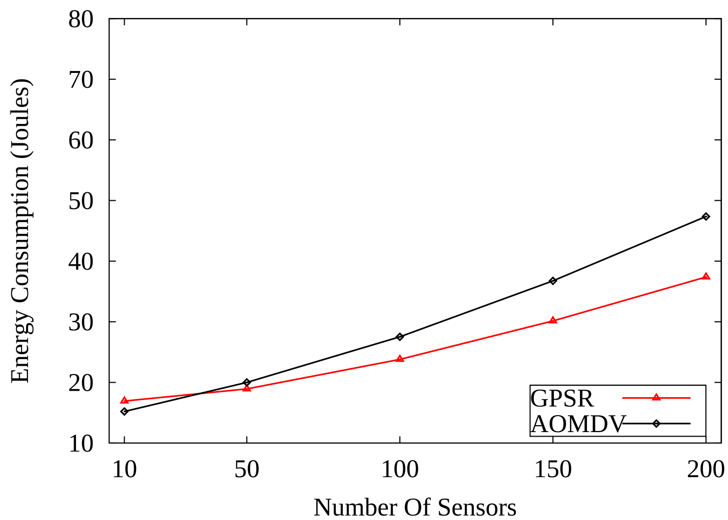


(b) Base-station is positioned at the center of the field.

Figure 6.6: Average hop count traversed by packet before it reaches destination.



(a) Base-station is positioned at the corner of the field.



(b) Base-station is positioned at the center of the field.

Figure 6.7: Average node energy consumption during whole network life time.

difference in energy consumption is due to the energy spent on communication. We can see that AOMDV consumes more energy than GPSR. This is due to the high routing overhead during route discovery process within AOMDV protocol (see Figure 6.5). In addition to route discovery, AOMDV uses periodic HELLO messages for link failure detection. This becomes clear when number of nodes is increased in case each node initiates its own route discovery process (since all nodes in MWSNs are source of traffic). GPSR consumes more energy than AOMDV when only 10 nodes are used. This due the nature of the GPSR protocol as when greedy forwarding fails, GPSR tries to forward packets along perimeter until packet is received or dropped with no destination found. As we discussed before, the position of base-station plays a major role in data delivery and protocol overhead and so on consumed energy by each node. Source node in AOMDV needs to search longer for the destination when base-station is positioned at field corner. Also, the path toward destination becomes longer (see Figure 6.6) which all is reflected on energy consumed by each node. In GPSR, packets traverse a longer path when base-station is position at field corner which increases energy consumed due to the routing role that each node plays.

6.2.6 Discussion

In this chapter we evaluated performance of two different MANET routing protocols, GPSR and AOMDV, to be used in mobile wireless sensor network. AOMDV is not well suited to work in MWSNs. Even with its ability to handle link breakage caused by node mobility (e.g. using multiple path routing), the nature of the traffic in MWSNs (all to one) produces a high routing overhead due to the route discovery process. This results in high energy consumption by limited energy nodes. GPSR performs well especially when network diameter is large enough (enough neighbors to each node). However, its dependency on geographic information propagation may needs consideration especially when used in critical applications (e.g military missions).

In general GPSR performs better that AOMDV due to its advantage of using geographic information that eliminate its needs for route discovery process used by AOMDV.

CHAPTER 7

CONCLUSION

In this chapter we conclude thesis by summarizing work done in previous chapters and investigate further work can be done in future.

7.1 Summary

In this thesis, many of existing mobile sensing systems is reviewed. Most of these systems target air quality monitoring applications as it is the case of OpenSense system. Most of them used direct data delivery mechanisms through existing mobile networks (e.g. 3G or GPRS data service) and few of them used opportunistic Wi-Fi connectivity for data delivery. We evaluated performance of a mobile wireless sensor network considering different data delivery scheme as used by previously reviewed systems. We also tested hybrid approach that use both exiting cellular network and available Wi-Fi coverage. We also used two MANET routing protocols, GPSR and AOMDV, for data delivery using an ad-hoc network formed between mobile sensors. We used two different sensing schemes, a threshold-based and energy-aware.

We found that MWSN performance is affected by the data delivery mechanism been used. Cellular (GPRS) and Hybrid (GPRS and Wi-Fi) approach performs similarly and outperform other data delivery mechanisms and the addition of Wi-Fi in the Hybrid approach improved energy consumption. Both AOMDV and GPSR perform badly in low network density. GPSR, however, outperforms AOMDV in medium and high density MWSNs due to its advantage of using geographic information for packets routing which cuts the need for the expensive route discovery process used by AOMDV. The energy-aware scheme helps in extending network lifetime with a little degradation in system performance because sensors become more conservative when their energy starts to deplete.

7.2 Future Work

Many issues need more investigation in addition to what we done in this thesis as in followings:

- We used two different mobility models, RWP and RPGM. In literature, there are many mobility models exist [38]. Performance of these models in location based sensing application need more investigation. We specifically interested in Manhattan mobility model, since it is more realistic in any vehicular mobile sensing system my take place in urban areas.
- We used GPSR and AOMDV routing protocols in an ad-hoc network formed by mobile sensor. GPSR performs well, but AOMDV has a high energy

consumption caused by its route discovery process which not suit MWSNs. Performance of mobile wireless sensor network need to be more investigated using another routing protocols or any other energy aware protocols.

- In this thesis, we focused only in energy consumed by sensing and communication units. Further investigation need to be done in energy consumed by localization since we used a location based application.

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